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Managing Trees on Arable Land

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List of Acronyms

µ	Mu, overall mean
µg	Microgram, unit of mass, 10^{-9} kg
µmol	Micromole, unit of amount of substance, 10^{-6} moles
A	Herbicide Mode of Action; Lipid Synthesis Inhibitors; ACCase Inhibitors
ACCase	Acetyl-CoA Carboxylase
AFS	Agroforestry System
ALS	Acetolactate Synthase
ANOVA	Analysis of Variance
ATP	Adenosine triphosphate, energy carrier in cells of organisms
B	Herbicide Mode of Action; Amino Acid Synthesis Inhibitors; ALS Inhibitors
B	Annual broadleaf weeds
BMEL	Bundesministerium für Ernährung und Landwirtschaft; Federal Ministry of Food and Agriculture
C1	Herbicide Mode of Action; Photosynthesis Inhibitors; Photosystem II Inhibitors
Ca	Calcium
CaCl2	Calcium chloride
c_{biogas}	Conversion factor for biogas
CH_4	Methane
cm	Centimeter, unit of length, 10^{-2} m
$c_{methane}$	Conversion factor for methane
CO_2	Carbon dioxide
CP	Chisel plough + ley crop
cv.	Cultivar
DAS	Days after sowing
DBH	Diameter at breast height (1.3 m)
DF	Degrees of freedom
DM	Dry matter
DMY	Dry matter yield
DS	Dry matter substance
dw	Dry weight
E	East
e	Residual error
e.g.	exempli gratia, for example
EE	Ether extracts
et al.	et alia, and others
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FNR	Fachagentur Nachwachsende Rohstoffe (FNR) e.V.
FVA	Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg; Forest Research Institute Baden-Württemberg
G	Annual and perennial grasses
GDD	Growing degree days
GS	Growing stage

h	Hour, unit of time
H_2S	Hydrogen sulfide
ha	Hectare, unit of area, 10,000 m²
HRAC	Herbicide Resistance Action Committee
HSD	Tukey's Honestly Significant Difference test
K	Potassium
K1	Herbicide Mode of Action; Seedling Root Growth Inhibitors; Microtubule Inhibitors
K3	Herbicide Mode of Action; Seedling Root Growth Inhibitors; Long-chain Fatty Acid Inhibitor
L	Liter, unit of volume
LA	Leaf area
LAI	Leaf area index
LEL	Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum Schwäbisch Gmünd
lm	Lumen, unit of luminous flux
LSD	Fishers Least Significant Difference test
LTZ	Landwirtschaftliches Technologiezentrum Augustenberg; Center for Agricultural Technology Augustenberg
m²	Square meter, unit of area
m³	Cubic meter, unit of volume, 10^3 L
m³sub	m³ solid under bark; equal to German term *Festmeter (Fm)*
Mg	Magnesium
Mg	Megagram, unit of mass, 10^3 kg
mg	Milligram, unit of mass, 10^{-6} kg
MgCl2	Magnesium chloride
MJ	Megajoule, unit of energy
mm	Millimeter, unit of length, 10^{-3} m
MLR	Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg; Ministry of Rural Affairs and Consumer Protection Baden-Württemberg
MP	Mouldboard plough
N	Nitrogen
N	North
n.d.	Not dated
N_2	Dinitrogen, moleculare nitrogen
N_2O	Nitrous oxide
NADPH	Nicotinamid adenine dinucleotide phosphate, reducing agent in anabolic reactions
NfE	Nitrogen-free extractives
nm	Nanometers, unit of length, 10^{-9} m
NT	No-till
O	Herbicide Mode of Action; Growth Regulators; specific site unknown
P	Phosphorus
p	p-value
PAR	Photosynthetically active radiation, spectral range of solar radiation from 400-700 nm that plants can use for photosynthesis
R	R programming language

R:FR	Red:Far-red ratio; 640 – 780 nm : 780 – 850 nm
Rep	Repetition
S	Sulfur
SAR	Shade avoidance response
SAS	Statistical Analysis System
SLA	Specific leaf area, ratio of leaf area to dry matter, $cm^2\ g^{-1}$
SP	Soil preparation
sp.	Species, genus known, species unknown
spp.	Species pluralis, plural of species of a genus
SRC	Short rotation coppice
ssp.	Subspecies of a species
VOCs	Volatile organic compounds
W	Woody species
WC	Weed control method
WSSA	Weed Science Society of America
XA	Crude ash
XF	Crude fiber
XP	Crude protein
y	Dependent variable
yr	Year

1. Introduction

1.1 Trees on arable land: Review and current status

The cultivation of trees on arable land is classified as Agroforestry System (AFS). In such systems an annual agricultural component (crop or livestock production) is combined with a perennial, woody component (trees, hedgerows), at the same time, on the same area of land (Nair, 1985). While in the temperate zone with an increasing mechanization in agriculture, the trees were removed from agricultural land and the cultivation of trees and crops was spatially separated, in the tropics and subtropics AFS continues to be the subsistence basis of smallholder agriculture.

However, agriculture is considered as one of the largest drivers of loss in biodiversity, with an increasing impact due to changes in consumption patterns and growing populations. Agricultural systems are considered to destroy biodiversity by converting natural habitats to intensely managed systems, increasing the output by an increase of harmful inputs (fertilizers, plant protection agents) and by releasing pollutants, including greenhouses gases like CO_2 and methane. When in 2019 the FAO published “The State of the World’s Biodiversity for Food and Agriculture”, the report highlighted the benefits associated with the conservation of biodiversity and ecosystems and highlighted the risks by their loss. They stated, that biodiversity makes the ecosystems more resilient against (climate) changes and can increase the food production, while limiting negative environmental effects, just to mention a few points (Bélanger et al., 2019). Kok et al. (2018) postulated in their study, that biodiversity will further decline, if the world stays on its current path of development. They offered three strategies to downshift further biodiversity losses. One of these strategies is the Decentralized Solution pathway, which will promote the “potential for ecological innovation in mixed land use systems where natural elements are interwoven within production landscapes” (Kok et al., 2018). Other authors also showed, that intensive cropping systems, which increase yields by higher resource inputs (fertilizer, plant protection agents, mechanization and irrigation) have negative impacts on biodiversity. To add a biodiversity effect in such systems, trees could be a possible solution (Barrios et al., 2018). Barrios et al. (2018) promoted that trees in AFS can create so called “hot spots of biological activity”.

To face the problems of monoculture and industrialization a reinvestigation of these AFS in intensified agricultural production systems offers an opportunity for biodiversity. Since AFS have a wide form of appearance, it was especially difficult to clearly characterize these systems in the past and make an area-based analysis. Hence, the data basis on AFS was very thin in the past. However, in recent years the area under AFS cultivation in Europe could be determined more precisely. In Europe, 22 % of the agriculturally used area is not covered by trees, whereas 40 % of the agricultural area is covered with >10 % trees, 23 % with >20 % trees and 15 % with >30 %. A comparison showed that these values correspond to those on a global scale. Globally, 46 % of the agricultural used area is covered with >10 % trees, 27 % with >20 %, 17 % with >30 % and only 10 % is not covered by trees (Zomer et al., 2009). From 2000 to 2010, Zomer et al. (2016) estimated an increase of 0.02 % in biomass carbon on agricultural land, which they equated to trees on agricultural land. Currently, 15.4 million ha in the European Union are AFS (den Herder et al., 2017).

Even today, in the tropics and subtropics, the simultaneous cultivation of trees and crops on the same field is the common form of land management. In Africa and Asia smallholder farming and the scarcity of land makes intercropping a widespread form of land management (Knörzer et al., 2010). If the crop and tree production is combined, this special form of intercropping is called Agroforestry. Nair (1985) defined the cultivation of trees and crops as a *silvoarable* or *agrosilvicultural* system, where an annual agricultural crop is produced together with a perennial, woody product (e.g. trees or shrubs as hedgerow intercropping, multipurpose trees or shrubs, shelterbelts, windbreaks, fuelwood). While this is the usual type of farming in equatorial climate zones, in the temperate zone most often the production of woody plants and agricultural products takes place on separate areas. But in the past, trees were also common on arable land in the temperate zone.

There were some well-known traditional systems, especially in Germany. Some of these traditional examples are the '*Streuobst*' (extensive managed fruit orchards with crop production or grazing between the trees) in the South, shelterbelts for wind protection in the North and East, so called '*Knicks*', and also the '*Hutewälder*' (wood pasture) (Chalmin, 2009a). Nowadays, the labor-intensive fruit production in the '*Streuobst*' orchards was replaced by commercial orchards and the wood pasture is no longer relevant for livestock. Shelter belts are still an interesting landscape object. But during the land consolidation in the 1970s and the trend towards the use of larger machinery, many of these systems have been lost. The targets of the land consolidation were the rearrangement of the existing rural property, improvement of the production and work conditions, and the support of the land management and regional development (FlurbG - Flurbereinigungsgesetz, n.d.). To form these large, uniform fields, the landscape with all existing landscape objects were cleared.

Farmers' interest in cultivating trees on arable land has increased again in recent years. In America and Europe, intercropping can cause yield stability, resource efficiency and sustainability (Knörzer et al., 2010). But, also the increase in biodiversity, reduced pressure by pests, diseases and weeds, habitat creation, erosion control, carbon sequestration and reduction in nutrient losses are possible advantages for farmers (Vandermeer, 1992; Montagnini and Nair, 2004; Rigueiro-Rodríguez et al., 2009).

The actual status of *silvoarable* AFS in Europe is shown in **Figure *1***. Especially in the Mediterranean region the cultivation of trees on arable land is practiced. 15,200 ha in Greece, 106,100 ha in Italy, 76,500 ha in Portugal, 117,000 ha in Spain and 5,700 ha in France are arable AFS, including agricultural production under permanent crops (fruit, nut and olive trees) and woodland and shrubland with sparse trees (Mosquera-Losada et al., 2016). Most of these AFS are traditional systems. Intercropping of orange (*Citrus sinensis* L.) orchards with leguminous crops, cereals or vegetables are a traditional form of AFS in Crete, Greece. If the trees develop a larger crown over the years, and thus more shade, poultry farming is carried out in the groves instead of agriculture (Pantera et al., 2016). In Italy, there are attempts to intercrop the old olive (*Olea europaea* L.) groves with wild asparagus (*Asparagus acutifolius* L.) or cut flowers (Rosati and Mantovani, 2015). The groves are no longer profitable due to the low revenue for olive oil. In Spain and Portugal the traditional system '*dehesa*' (spanish) or '*montados*' (portuguese) exist, which is a wide pasture for pigs and cows under holm-oaks (*Quercus ilex* L.), but also cereal production (wheat, oat, barley, rye), most often for fodder, takes place (Moreno and Cáceres, 2016). In France, there are huge areas of intercropped walnut (*Juglans* spp.) orchards in the Dauphiné province in the Southeast. The intercropped products range from cereals (*Triticum* sp., *Hordeum* sp.) to fodder (*Medicago sativa* L.) to oil crops (*Helianthus annuus* L., *Glycine max* (L.) MERR., *Lavandula* sp.) and root crops (*Zea mays* L., *Sorghum* sp., *Nicotiana* sp.). In this region, the walnut trees are intercropped for about 10 years. Smaller fruit trees (*Malus domestica* BORKH., *Ribes* sp.) or vineyards (*Vitis vinifera* L.) for more than 12 years. The traditional cultivation of walnut trees only for fruit production has been shifted in the last decades to a dual-production of fruits and high-valuable timber (Mary et al., 1999).

Especially in the Mediterranean area AFS survived due to productive, symbolic and environmental reasons. These systems created a landscape that made arable farming possible (e.g. construction of terraces for better water infiltration, reduced erosion) (Kizos and Plieninger, 2008). Kizos and Plieninger (2008) also stated, that these Mediterranean systems are important for the local identity, since factors like “local” and “quality” gains more attention. Also, the Mediterranean AFS landscapes were formed over thousands of years and besides the additionally income from fruit and wood, the trees provide shade for livestock and workers in this area. In the opinion of famers of marginal areas, AFS is the most suitable form of land cultivation for these areas. Nowadays, other usage, like wood, gains also interest (Lovrić et al., 2018).

The above-mentioned systems are mostly traditional AFS, but there are already (research) approaches for modern systems. So, in France the cultivation of timber trees (*Populus* spp., *Juglans nigra* x *regia*, *Prunus domestica* L., *Fraxinus excelsior* L., *Acer* spp., *Celtis australis* L., *Pyrus pyraster* (L.) DU ROI) aligned in rows within arable fields of 35 ha are established (Gosme et al., 2016). In the valley of Po, Italy, 10 ha of Poplar hybrids (*Populus* x *canadensis* MOENCH) for timber and energy wood production with diverse cereals and root crops are grown (Paris et al., 2016). Other approaches are poplars, walnut and cherry (*Prunus avium* L.) for high-valuable timber production with grapevines, cereals, alfalfa, vegetables, and common beans in Voio, Greece (Mantzanas et al., 2016).

In temperate zones *silvoarable* AFS does not cover wide areas as seen in the Mediterranean region (**Figure *1***). Except of Cyprus and Portugal, most of the European countries have less than 1 % of their agricultural used area classified as AFS. Some examples for silvoarable AFS can be found in the United Kingdom (2,000 ha), Hungary (2,000 ha), Switzerland and Germany (5,700 ha) (den Herder et al., 2017). In the United Kingdom, in recent years, alley cropping of trees for timber production, as Short Rotation Coppice (SRC) or for fruit production with arable or horticultural crops gained popularity. One of the reasons is the function as shelterbelt (Smith et al., 2015). In Hungary shelterbelts were traditional landscape objects, but the number of these systems is declining. There are research approaches of alley cropping trees for woodchips, timber or fire wood with crops for fodder production (Vityi et al., 2015). In Switzerland, trees were always part of the landscape and were combined with agriculture. However, many of these trees were felled in the 1930s to 1970s. Today, however, farmers have interest in establishing trees on their land, e.g. for fruit production, as SRC, or as high-valuable timber. For example, winter wheat, sorghum, maize or even field vegetables are used as arable crops between the tree rows (Petrillo et al., 2016). With beginning of the 18th, century the large-scale cultivation of ‘*Streuobst*’ has arose in Germany. The density of fruit trees in 1900 where 4.8 trees per hectare in the German Empire. The four main species were apples, pears, plums (*Prunus* spp.) and cherries. In 1930, '*Streuobst*' reached its maximum (Herzog, 1998). Nowadays, there are 116,000 ha '*Streuobst*' with 9.3 Million trees in the German state of Baden-Württemberg (Ministerium für Ländlichen Raum und Verbraucherschutz, 2015). Since fruit production in half-standard plantations is more efficient and economical, these systems decline. One possibility of further use is the transfer of these extensive managed fruit orchards in so-called '*Wertholzwiesen*'. The replanted trees are no longer cultivated for fruit production, but for high-valuable timber. Another possibility is the cultivation of such trees in *silvoarable* systems (Brix et al., 2009; Chalmin, 2009b).

Therefore, many traditional systems are intended to be preserved (e.g. intercropped orange orchards, olive grove Italy), converted to modern usage (e.g. Walnut production in France) or new systems being created (e.g. high-valuable timber AFS in Germany, energy SRC in United Kingdom).

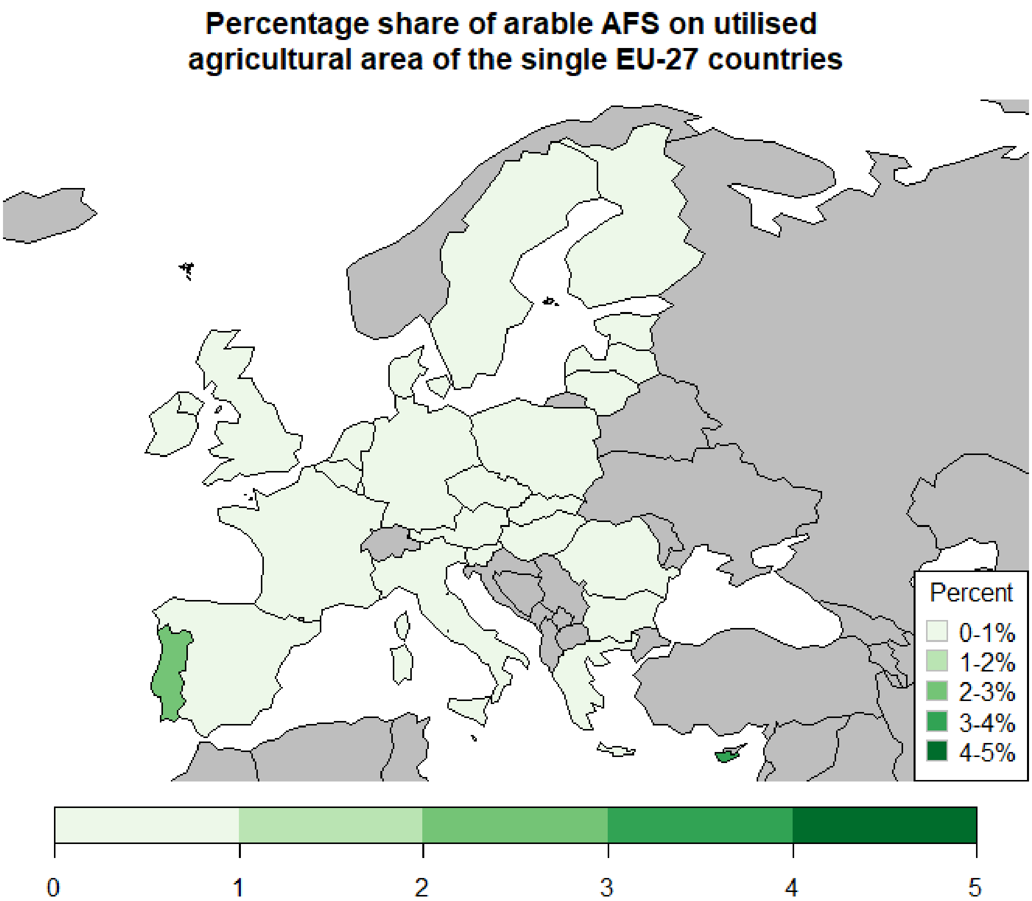

Figure 1: Percentage share of arable AFS on utilized agricultural area of the single EU-27 countries (own figure, based on data of den Herder et al. (2017)).

For farmers, it is crucial to know how to create such an AFS. An important aspect is to ensure the successful growth of the trees, since only through a successful establishment additional income and profit can be generated in the following years.

1.2 Recommendations for establishment of trees on arable land

If farmers decide to plant trees on their agricultural land, there are numerous production issues, which need to be clarified. One of these is the form of establishment, which varies according to the final usage of wood. Possible tree usages could be for timber usage or for wood chip production. Such tree strips can promote the biodiversity by providing habitat for a diversity in flora and fauna. Schroth et al. (2004) and Willemen et al. (2013) observed that AFS can increase the complexity of the landscape and create pollinator-friendly habitats. For timber tree usage the additional advantage is, that trees can be planted that no longer grow in the landscapes, and become more common again. Flower mixtures can be sown into the tree strips too, which generate a food resource for wild bees and other insects. A study from Switzerland showed a proportion of diverse ground beetle species in flowering strips that was more than double than those in arable fields (Lys and Nentwig, 1992). In southwest Germany, flower mixtures showed a total of 58 wild bee species, which use the strips for nesting or as fodder resource (Engels et al., 1994). A three-year rotation of short rotation coppice for wood chip production does not provide such a long-lasting habitat than undisturbed valuable timber tree strips, but it is longer undisturbed than an agricultural used field. A SRC also offers a more regular yield than timber trees. Depending on tree age, choice of trees (tree crown shape), plantation size and location / accompanying structures 8 – 60 species of birds can be found in SRC, compared to arable fields, where less than 30 % of the species richness found in SRC were present (Schulz et al., 2009). While the establishment of single trees for fruit or high-valuable timber is fairly easy, establishing trees (strip wise) as Short Rotation Coppice requires an adequate soil preparation and weed management to keep weed pressure low. This ensures growth and high final biomass yields.

To generate tree strips that provide such a habitat function, it is important to create an initial growth phase which is free of weed competition. If trees for high-valuable timber production are planted on agricultural land, weed competition is not much of a concern. Since trees are used for planting which are already high (‘*Viertelheister*’; quarter-standard tree, 1.25 – 1.50 m height or ‘*Halbheister*’; half-standard tree, 1.50 – 2.00 m height), weed suppression will be unusual. However, if a SRC should be established, a site adapted soil tillage and weed management is crucial. Although, a SRC can be created with long rods / whips (‘*Setzstangen*’, 2 – 4 m long), this method is more complex in planting and more expensive than the use of cuttings (‘*Steckhölzer*’, 20 – 25 cm long). When cuttings are used only 1 – 2 cm protrudes above soil level (Verwijst et al., 2013). Therefore, the cuttings can be quickly suppressed by weeds. The control of the accompanying vegetation prior planting is essential (Department for Environment Food and Rural Affairs (DEFRA), 2004). Especially for willow SRC weed control is of crucial importance for successful establishment and success of plant survival (Möller et al., 2007). It is an important aspect in order to achieve successful tree growth and later high biomass yields.

The literature has shown that the most common form of establishment is ploughing in autumn (30 – 40 cm depth) and a secondary tillage (25 cm depth) prior planting. Herbicide applications with *Terbuthylazine* should be done directly after planting or an application with *Glyphosate* prior planting on sites with high weed infestation (Möller et al., 2007). Other literature recommends at least two to three herbicide applications. The first one in mid-summer, prior planting year, the second one in autumn and, if necessary, a third application on strong weed infested sites prior planting (Tubby and Armstrong, 2002; Department for Environment Food and Rural Affairs (DEFRA), 2004). They also recommend a glyphosate-based chemical weed treatment.

The combination of ploughing and secondary tillage is efficient for creating a well rooted seedbed and minimize weed competition. Other types of soil tillage and weed control have other advantages. A reduced tillage with ley crop or no-till can be interesting if the SRC strips should be established on steep, erodible slopes or as riparian (riverside) buffer strips along surface water bodies. Additionally, a ley crop provides and conserves nitrogen, reduces soil erosion, reduces weed pressure, and increases soil organic matter content (Hartwig and Ammon, 2002). It enriches soil with essential mineral nutrients, improves soil structure, increases the soil’s biological activity, conserves soil moisture, and decreases diseases and insect problems (Fageria et al., 2005).

Soil tillage is the first step towards an optimal establishment. However, additionally weed control may be necessary depending on the planting site and tillage used. Different weed management methods offer different advantages. The **chemical** broadcast application of pre-emergence herbicide Terano (*Metosulam, Flufenacet*) / Stomp (*Pendimethalin*) and post-emergence herbicide Fusilade Max (Fluazifop-p-butyl) / Lontrel 100 (*Clopyralid*) is well-proven in practice. Additionally, the broadcast-application of a soil-herbicide in pre-emergence was tested (Sencor WG; *Metribuzin*) and two alternative post-emergence herbicides (Katana; *Flazasulfuron*, Kontakt 320 SC; *Phenmedipham*). To promote biodiversity, a reduction of plant protection agents is a possible option. Some studies showed, that herbicides decrease the amount of pollinators in agricultural landscapes, by habitat-fragmentation and erasing food resources (Kovács-Hostyánszki et al., 2017). If fewer weeds exist due to herbicide applications, pollinators find less food. Especially wild bees and bumble bees are highly specified on some rare plants. If these weeds are killed by chemical plant protection, their fodder resource is eliminated (Marshall et al., 2003; Gaba et al., 2016). Another aspect is, that the usage of herbicides can generate resistances, which results in a fewer availability of plant protection agents (Heap, 2009). This decrease in herbicide amounts cannot be compensated by newly developed agents, because a trend is observable, that the amount of new plant protection patents is decreasing (Bonanno et al., 2017).

Based on these facts there is a need for reduced or non-chemical weed treatment. Therefore, combinations of **chemical and mechanical** weed treatment with the practicable herbicides as intra-row band-spraying, and inter-row mulching, rotivation and rolling were tested. The herbicide application only as intra-row band-spraying can reduce the herbicide amount. Mulching, as a ground cover, is a barrier to germinating weeds, and prevents light from reaching the ground (Tu et al., 2001). Rotary hoe or rotivation shifts the weed seeds up on the soil surface where they dry out, buries them with soil and also shreds the weed roots and rhizomes (Place and Reberg-Horton, 2008). Herbicide rolling via roll coating apparatus ‘Rotowiper’ avoids the application and drift of herbicides on non-target plants (like the rows with willow cuttings) (Harrington and Ghanizadeh, 2017). As a **non-chemical, mechanical** weed control, suitable also for organic farming, wood chip mulch was tested. Wood chip mulch influences weed germination by light and temperature reduction, and also acts as a barrier (Jodaugienė et al., 2006). It suppresses weeds by coverage, and by leaching of allelochemical compounds (Rathinasabapathi et al., 2005; Kefeli and Kalevitch, 2013).

After the successful establishment of trees on arable land, they compete for light, water and nutrients with the understory agricultural crop.

1.3 Influence of shade on plants; growth, yields, qualities

If there is a combined cultivation of trees and crops on the same area, at the same time, there is a multiplicity of interactions between each other. One of the most noticeable effects caused by trees is the shade, which they cast on the understory crop. There are crops that can cope with this shade better than others.

Light energy is of crucial importance for plant growth (Franklin and Whitelam, 2005). It is used in their metabolism to produce carbohydrates (Casal, 2012). When plants are shaded, they respond with a variety of adaption strategies. Some of these shade avoidance responses (SAR) are a reduced branching, reduced biomass, increased height, decreased leaf number, higher specific leaf area and a reduced yield per plant (Carriedo et al., 2016). Most of the harvested sink organs of plants (e.g. grains and tubers) consists mainly of carbohydrates (White et al., 2016). If shade affects the carbohydrate metabolism, there will be change in the yield of the plants.

As mentioned in **Chapter 1.1**, most of the AFS is done in the tropics and subtropics. Due to their geographical location at latitudes near to the equator, these regions receive more solar irradiance. The tropics receive up to 30 MJ m^{-2} day^{-1} of solar irradiance, which is about 50 % more than the temperate zone (NASA, 2018). So, under the tropical conditions there is more solar irradiance available to reach the light saturation point of crops, even when shaded by trees. Shaded potatoes in the tropics and subtropics showed increased tuber yields under shade (Sun and Dickinson, 1994; Kareem, 2007; Mariana and Hamdani, 2016; Nadir et al., 2018). Maize, on the other hand, showed reduced biomass yields under shade (Singh, 1994; Peng et al., 2009). In the temperate zone the lower irradiance, in combination with shading, may results in irradiance conditions where the light saturation points of the crops cannot be reached. So far, there is little literature on the influence of shade on growth, yield and quality on arable crops in temperate zones. The few studies that focused on this aspect suggest, that some plants are better suited, than others, and that the plants differ greatly in their tolerated shade level. While soybeans, peanuts, wheat, maize, beans and rice showed reduced yields under shade (Khybri et al., 1992; Newman et al., 1997; Ceccon, 2008; L. Gao et al., 2013; Zhang et al., 2013), shade can have both, reducing and increasing effects on plant ingredients. While the yield of some C3 fodder grasses (e.g. *Poa pratensis* L., *Lolium perenne* L., *Bromus inermis* Leyss. or *Festuca arundinacea* Schreb.) decreased under 80 %, they showed a significant higher content of crude protein than those grasses grown under full sunlight (Lin et al., 2001a).

So, the assumption is, that maize (*Zea mays* L.) as a C3 plant with a high light saturation point is more shade-intolerant, than potato (*Solanum tuberosum* L.) as a C4 plant with a lower light saturation point (Pleijel et al., 2002; Puntel, 2012). Especially, at AFS in higher latitudes, this high light saturation point in combination with shade can cause some crops to grow only to a certain level of shade / age of trees. This influence of shade should be exemplified by the two crops maize and potato.

1.4 Hypothesis

The present doctoral thesis focused on the management of trees on agricultural land. If trees are planted on agricultural land, this can pose great challenges for the overall management for farmers. Especially, when a SRC should be established. Up to date, the most practiced method for establishment is moldboard ploughing with chemical weed management. Less information about alternative establishment methods can be found. There is also little expertise how plants and yields act under reduced forms of soil tillage and the use of other weed managements than herbicides prior or directly after planting. The two major aims were to investigate (i) the most suitable combination of tillage and weed management in an agroforestry system with tree strips for energy wood production to enable the trees a youth phase free of weed competition; and, (ii) the competitive situation created by trees for agricultural crops and the impact on crops.

Following these, the thesis aimed to test the following experimental hypotheses:

- The selection and combination of soil tillage and weed management in a **willow SRC** will have a major effect on plant development and final biomass yield. Due to different types of soil tillage variants (turning / non-turning), weeds from different soil layers can germinate. Depending on the combined weed treatment, the weeds are controlled in a variety of ways. Some tillage methods only enable a competition free establishment phase under a certain weed treatment, and vice versa. Therefore, soil tillage and weed management must be sufficiently coordinated. So, it is hypothesized, that the practiced establishment system for SRC of mouldboard ploughing and a broadcast herbicide application of a mixture with a wide spectrum of activity, generates higher final biomass yields, by enabling a weed competition free youth development of the cuttings, in contrast to the combination of a reduced herbicide application, with a limited spectrum of activity and a partial or non-herbicide application or a reduced or no-till soil cultivation.
- If the standard system for SRC establishment of mouldboard ploughing and broadcast application of a wide herbicide activity spectrum is replaced by other establishment combinations of soil tillage and weed control, final biomass yield will be lower due to the non-weed free and so competitive youth development.
- If an SRC or high-valuable timber trees are established at the same time, on the same area of land, the tree shade will affect different crops differently:

    - The C4 species maize is intolerant to shade due to its high light saturation point near full sunlight. If maize plants are shaded during growth, there will be a decrease in biomass yield and quality-determining parameters due to a reduced photosynthesis rate.

    - Potato as a C3 species, with a moderate light saturation point, is tolerant against shade during growth. If some plants are shaded, while others remain unshaded, there will be no difference in yield and quality between the treatments.

For the investigation of these hypotheses two field trials were established within two research projects. The results gained were used to prepare three scientific articles (**Chapter I – III**), which represent the body of this thesis.

The trial in **Chapter I** was established at the experimental station 'Ihinger Hof' of the University of Hohenheim in the edaphoclimatic area of the Black Forest, southwest Germany. It was funded by the Ministry of Rural Affairs and Consumer Protection Baden-Württemberg (MLR), within the project "Biomasse aus Kurzumtrieb" (grant number 0319E), which was a cooperation between the Centre for Agricultural Technology Augustenberg (LTZ) and the Forest Research Institute Baden-Württemberg (FVA). The field experiment was planted in 2010 and the first harvest took place in 2013. The three different soil tillage methods, consisting of mouldboard plough, chisel plough + ley crop and no-till, were combined with eight different weed management practices, including chemical, chemical + mechanical and mechanical treatments. Establishing a willow SRC with mouldbaord ploughing and a chemical weed treatment meets the actual cultivation recommendations. The combination of alternative, fuel-saving soil tillage systems and other, herbicide-saving weed management systems, might be of great interest in times of climate change and biodiversity loss. Therefore, **Chapter I** deals with alternative, resource-saving establishment methods for a successful growth of a willow SRC. In addition to tree height, survival rate and yield, other parameters such as diameter at breast height and weed coverage were determined. The **Chapters II** and **III** represent the results of the research project 'Agro-Wertholz: Agroforstsysteme mit Mehrwert für Mensch und Umwelt', as well as further studies on plant development under shade. The project was realized in cooperation with the Chair of Forest Growth and Dendroecology and the former Chair for Landscape Management, both University of Freiburg, and the Centre for Agricultural Technology Augustenberg. Funding was done by the Federal Ministry of Food and Agriculture (BMEL) through the project agency Fachagentur Nachwachsende Rohstoffe (FNR) e.V. (grant number 2201514). Therefore, in 2015 a field experiment was established at the experimental station of the Centre for Agricultural Technology Augustenberg (LTZ) in the edaphoclimatic area of Rhine and side valleys in southwest Germany. The field experiment consisted of an artificial shading system, which created shade by nets, stretched between wooden post. Over a period of three years the amount of solar irradiance for the crop growing below the nets was reduced by these nets during the growing period. In addition to the yield and quality analyses done within the project, **Chapter II** and **III** also focused on plant growth and the change of individual growth parameters by shade on the shade-intolerant agricultural crop maize and the shade-tolerant crop potato. The general discussion extends the scope to aspects, that could not be mentioned in **Chapter I – III**. The effects of alternative establishment methods will be discussed in context of the shifts in the weed seed bank by different tillage systems. Under no-till or chisel plough a higher amount of weed seeds is found in the upper soil layers and can germinate. Under mouldboard plough these seeds will be transferred to deeper layers, which inhibits germination. The weed treatment methods will be examined in the context of the mode of action of the used herbicides and the mechanisms of the mechanical weed treatments. In pure chemical weed treatments, a broad spectrum of mode of actions is recommendable, while mechanical treatments can be an option under mouldboard ploughing and no-till. The ley crop under chisel ploughing creates too much competition for the willow cuttings. The shade studies showed, while maize can be recommended up to shade levels of 26 %, potato can gain adequate yields at levels of 26 – 50 % shade, depending on the annual weather conditions. Several worldwide important agricultural crops beside maize and potato were discussed for their growth and yield under shade. Which showed, that none of them had an increase in yield by shade. Shade reduced the yield or it remained the same due to adaption reactions in the plants, which affect the quality of the harvested material. Additionally, to the shade influence in **Chapter II** and **III** the influence of the other two main influence factors in AFS, water and nutrients, on maize and potato will be discussed. These considerations showed, that trees and crops compete in the areas near the tree strips for the same pool of water (and so for the same nutrients, because most nutrients are taken up via mass flow). It also showed, that in the temperate zone with a good supply of water and nutrients, but lower solar irradiance due to higher latitudes, the competition for light will be the main limiting factor. An economic assessment of the performance of an AFS consisting of tree strips for SRC and high-valuable timber was done for maize and potato, which revealed that strips for SRC are unprofitable in a one hectare-sized AFS. Potatoes are shade-tolerant in systems with shade levels between 26 - 50 %, but due to high market prices, even the reduction by the area of the tree strips are already too high to be profitable. An ecological performance of AFS has been done for the factors carbon sequestration, biodiversity conservation, soil enrichment, and air and water quality. The investigated one hectare-sized AFS for SRC would be able to save 11 Mg ha^{-1} carbon. The tree strips provide habitat and food for birds and divers insects. Also, erosion and leaching can be reduced. Further research approaches, that appeared while working on this thesis, were also included in the general discussion, like the need for dynamic shade simulation, studies in older AFS and the testing of plants for non-edible purposes, which have their origin under shady forest conditions. The primary results of the **Chapters I-III** have been submitted to peer-reviewed journals. All papers have been published.

2 Publications

The present cumulative thesis consists of three different papers as reflected by **Chapters I – III**, which represent the key elements of the dissertation. **Chapter I** - **III** have been published in peer-reviewed, international referenced journals.

Chapter I

Schulz, V., Gauder, M., Seidl, F., Nerlich, K., Claupein, W., Graeff-Hönninger, S. (2016): Impact of different establishment methods in terms of tillage and weed management systems on biomass production of willow grown as short rotation coppice. Biomass and Bioenergy 85, 327-334.

Chapter II

Schulz, V.S., Munz, S., Stolzenburg K., Hartung J., Weisenburger S., Mastel K., Möller K., S., Claupein, W., Graeff-Hönninger, S. (2018): Biomass and Biogas Yield of Maize (*Zea mays* L.) Grown under Artificial Shading. Agriculture 8(11), 178.

Chapter III

Schulz, V.S., Munz, S., Stolzenburg K., Hartung J., Weisenburger S., Graeff-Hönninger, S. (2019): Impact of different Shading Levels on Growth, Yield and Quality of Potato (*Solanum tuberosum* L.). Agronomy 9(6), 330.

3 Chapter I

Impact of different establishment methods in terms of tillage and weed management systems on biomass production of willow grown as short rotation coppice

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Publication I:

Schulz, V., Gauder, M., Seidl, F., Nerlich, K., Claupein, W., Graeff-Hönninger, S. (2016): Impact of different establishment methods in terms of tillage and weed management systems on biomass production of willow grown as short rotation coppice. *Biomass and Bioenergy, 85*, 327-334.
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If trees should be cultivated successfully on agricultural land, a site-adapted combination of tillage and weed management is needed, to ensure a proper establishment of the trees or Short Rotation Coppices cuttings. A well-adapted establishment is the precondition for a good youth development of the trees and, thus, the overall yield. Many studies on using willows for Short Rotation Coppice have been carried out in recent years. These studies aimed at optimizing yield by improving planting density or to test different cultivars. However, little information is available on site-adapted establishment methods. Facing this background, Chapter I focuses on different establishment methods for maximizing Short Rotation Coppice yield. Special attention was paid on the competition of weeds, which should already be reduced by tillage. The study tested three tillage systems (mouldboard plough, chisel plough + ley crop, no-till) on a Luvisol soil in southwest Germany. Tillage systems were combined with eight weed management treatments (chemical, chemical + mechanical and mechanical). Different parameters, such as survival rate, weed coverage as well as growth parameters like plant height and diameter at breast height were determined. Significant differences in growth of willows were determined between the different establishment methods. These differences were also reflected in the final yield at harvest after three years.

https://doi.org/10.1016/j.biombioe.2015.12.017

4 Chapter II

Biomass and Bioenergy Yield of Maize (*Zea mays* L.) Grown under Artificial Shading

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Publication II:

Schulz, V.S., Munz, S., Stolzenburg K., Hartung J., Weisenburger S., Mastel K., Möller K., Claupein W., Graeff-Hönninger, S. (2018). Biomass and Biogas Yield of Maize (*Zea mays* L.) Grown under Artificial Shading. *Agriculture, 8*(11), 178. https://doi.org/10.3390/agriculture8110178.

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*If trees and agricultural crops are combined at the same time, on the same area of land, the shade of trees is expected to influence growth and development of the understory crop. Some crops are considered to be more shade-tolerant than other crops and might offer a higher suitability to be grown in these systems, than other crops. Maize, as a C4 plant, is considered to be intolerant to shading. Literature showed that shade reduced significantly the growth and development and, thus, the final yield of maize. However, little information is available on silage maize and the potential impact of shade, especially on the final biomass quality. Additionally, most of these experiments were carried out in tropical and subtropical countries, were a higher light availability is given, even under shade, when compared to temperate zones. Chapter II deals with the influence of different levels of shade on the growth, yield and biomass quality of maize (*Zea mays *L.) for biomass and biogas production in the temperate zone. Within the study, the incoming solar irradiance was reduced by shading nets about 0 %, 12 %, 26 % and 50 % at an experimental location in southwest Germany. Different growth parameters, known to determine final biomass, were determined, and also the change on the composition of final biomass. Biogas and methane potential were calculated from biomass yield and chemical analyses. The final aim of this chapter was to (i) evaluate the impact of three shade levels (12 %, 26 %, and 50 %) on maize growth and biomass yield; (ii) determine the effect of shade on biogas and methane forming parameters; and, (iii) to determine the effect of these shade levels on the final biogas and methane yield.*

agriculture

MDPI

Article

Biomass and Biogas Yield of Maize (*Zea mays* L.) Grown under Artificial Shading

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Abstract: Agroforestry, as an improved cropping system, offers some advantages in terms of yield, biodiversity, erosion protection or habitats for beneficial insects. It can fulfill the actual sustainability requirements for bioenergy production like food supply, nature conservation, stop of deforestation. However, competition between intercropped species for water, nutrients and light availability has to be carefully considered. A field trial with shading nets was conducted in Southwest Germany to evaluate the influence of different shading levels (−12, −26, and −50% of full sunlight) on biomass growth, dry matter yield and biogas quality parameters of maize (*Zea mays* L., cv. 'Corioli CS'). Shading the plants causes a delayed development, a reduction in height and leaf area index and a slower senescence. Dry matter yields were reduced about 18%, 19%, and 44% compared to 21.05 Mg ha^{-1} year^{-1} at full sunlight. Biogas and methane yields were also significantly reduced, the 50% shading treatment showed a reduction of 45% for both parameters. Further, shading led to higher crude protein and crude ash contents. If silage maize is grown under shade, the yields of dry matter, biogas, and methane are nearly halved under 50% shade. Cultivation up to 26% shading could be possible.

Keywords: maize (*Zea mays* L.); agroforestry; biogas; shade; yield; growth; quality

1. Introduction

By 2020, 20% of the produced energy in Europe must be generated from renewable sources [1]. Hence, the area of plants grown for biogas production is steadily increasing. In Germany, the most commonly used crop for biogas production is silage maize (*Zea mays* L.) with a cultivation area of one million ha in 2016 [2]. Maize is a highly attractive crop for biogas production due to high biomass yields and methane yields between 7500 to 10,200 m^3 ha^{-1}, which has not been achieved by any other crop used for biogas production so far [3].

The increased cultivation of maize in monocropping systems has led to several environmental problems including a loss of biodiversity, increased nitrate levels in water bodies and soil degradation [4]. The implementation of maize intercropping systems could alleviate some of the problems related to maize monocropping. Intercropping systems could have several advantages; such as increased productivity; reduced pressure by pests, diseases, and weeds; higher carbon sequestration; and reduction in nutrient losses [5–7]. One particular type of intercropping system are silvoarable agroforestry systems (AFS) which combines annual crops with perennial, woody plants. Widely used crops for AFS are fast growing trees like willow (*Salix* spp. L.) or poplar (*Populus* spp. L.) as a short rotation coppice [8–12]. Alternatively, trees for high-value timber production can be used as shown in trials conducted in Canada, France, and the Philippines [13–17].

Within an AFS, interactions between the intercropped species occur in terms of competition for light, water, and nutrients [18,19]. The competition for light could lead to a considerable reduction in plant growth and yield, especially for maize, which is known to be a shade-intolerant C_4 species [16]. Further, delayed development and lower leaf emergence rates have been observed for maize when shaded at different growth stages. In an intercropping of maize and wheat, the tassel initiation and silking was delayed compared to the monocrop equivalent. Additionally, the interval between anthesis and silking was prolonged by shading [20]. This effect was also observed by Early et al. [21], who showed a delay in the emergence of tassel, anther, and silk; when the plants were shaded at levels of 30%, 60%, 70%, 80%, and 90%. In addition, shading reduced the plant height of maize [21]. A study by Syafrullah et al. [22] revealed that some light-sensitive maize genotypes intercropped with oil palms showed a decreasing plant height with shading from 22%, 37%, to 76%. Also, significant height reductions were observed at a distance of 2 m from the trunks of 10 to 12 m high maple (*Acer* spp. L.) and poplar trees (*Populus* spp. L.) compared to measurements at a distance of 6 m. Furthermore, shading can also reduce the whole plant leaf area of maize [16]. In a dense plant stand (9 to 12 plant m^{-2}) in which maize plants shade each other more than compared to a stand with 3 plants per m^{-2}, maize plants showed a significant decrease in leaf length and leaf width and, in turn, in leaf area [23]. Another study showed that unshaded leaves were larger than shaded leaves [24]. These growth changes will ultimately impact biomass. Under 20% of full sunlight, a reduction in total dry weight of maize was observed [25]. Growing maize at 1.0 to 2.5 m distances from 3 m high walnut (*Juglans regia* L.) and plum trees (*Prunus salicina* Lindl.) resulted in a reduction of total aboveground biomass by 29 and 41%, respectively [26].

Besides the impact of shade on maize growth and, thus, final biomass, a reduction of light also has an impact on plant composition components. The individual composition components contribute differently to biogas and methane formation. From one kilogram of carbohydrates 790 L of biogas with a quantity of approximately 50% methane can be obtained. For fat the values are 1250 L and 68%, and for proteins 700 L with 71% methane [27]. If the plant composition is changed under shade this will affect biogas and methane yields. For instance, Jia et al. [28] observed an increase in protein and fat content in maize grains under a 55% light reduction. Fat (also named ether extracts because it contains plant parts that are soluble in ether) consisting of fats and fatty acids, have the longest hydraulic retention time in the biogas process, but apart from protein, they contribute the most to the methane yield [29]. Studies with shaded soybeans and maize also observed an increased protein content with increasing shade [30,31]. A study by Singh [25] observed a rise in protein content as well as a decrease in cellulose by 80% shade. There could have been a poor synthesis of cellulose in cell walls due to shade. He also observed that sugar and starch, which could be grouped as nitrogen-free extractives, increased under shade in maize stems, due to a poor translocation. High contents of sugar and protein can cause acidification, resulting in an inhibition of biogas and methane production [32]. Under the shade of ponderosa pines (*Pinus ponderosa* P. Lawson & C. Lawson), Kentucky bluegrass (*Poa pratensis* L.) showed higher contents of crude ash [33]. High contents of ash reduce methane production due to lower amounts of biodegradables [34].

Shading can also affect the concentration of macronutrients in plant tissue. For instance, shading of 63% on cotton (*Gossypium hirsutum* L.) led to an increase of phosphorus and sulfur in leaves, buds, and bracts [35]. Two forages, crested wheatgrass (*Agropyron cristatum* L.) and basin wild rye (*Leymus cinereus* Scribn. & Merr.) showed a higher content of potassium, calcium, and magnesium under 75% of shade [36]. Potassium is needed for oxidative activity of the methanogenic archaea, but at high concentrations, the increase of osmotic pressure can lead to stress. The high salt content of the fermenter medium causes water diffusion out of the archaea cells. The cells dehydrate wherefore the archaea die, causing a decline in biogas production [37]. High contents of calcium can lower the protein and fat removal and inhibit the anaerobic digestion [38]. For normal functioning of the biogas and methane formation, there are critical values for some of these macronutrients, such as 3 mg m^{-3} potassium, 2.8 mg m^{-3} calcium ($CaCl_2$), 2.400 mg m^{-3} magnesium ($MgCl_2$), and 20–50 ppm for sulfur (H_2S) [39,40].

If solar radiation is one of the main growth factors for plant growth and some maize plants for biogas production are shaded while others remain unshaded, then the plant growth, yield, quantity, and quality of biogas yield from shaded plants will be lower than in plants grown under full solar radiation. To the best of our knowledge, there has been no published study investigating the effects of shade on maize and, ultimately, the impact of biogas and methane yields. Therefore, the objectives of this study were to: (i) evaluate the impact of three shade levels (12%, 26%, and 50 %) on maize growth and biomass yield; (ii) determine the effect of shade on biogas and methane forming parameters; and, (iii) determine the effect of these shade levels on the final biogas and methane yield.

2. Materials and Methods

2.1. Study Site and Experimental Design

The experiment was conducted in Southwest Germany in the lower Rhine valley at the experimental station of the Centre for Agricultural Technology Augustenberg (LTZ) in Rheinstetten-Forchheim (48°58′ N, 8°18′ E, 117 m above sea level (a.s.l.)). The mean long-term precipitation is 742 mm $year^{-1}$ with an average temperature of 10.1 °C. During the growing season (March–October), the average long-term precipitation is 509 mm. The year 2015 was drier than 2016 with only 223 mm of precipitation compared to 361 mm between April and August (Figure 1). In 2016, high rainfalls occurred in early summer (April–June); however, July and August were rather dry. Similar to 2016, rainfalls in 2017 were more evenly distributed.

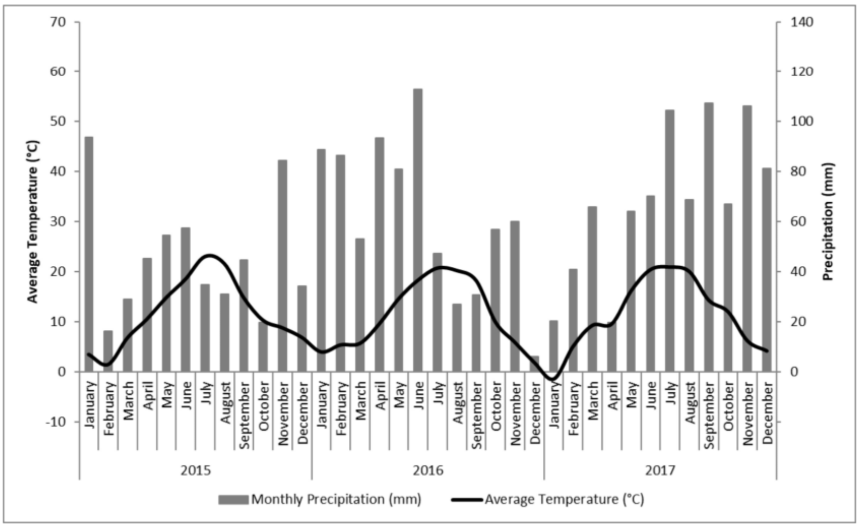


Figure 1. Average temperature (°C) and monthly sum of precipitation (mm) during the three experimental years 2015 to 2017.

The experimental soil was a Luvisol with a texture of 13.7% clay, 60.2% sand, and 26.1% silt in 0–90 cm. Additional soil characteristics are listed in Table 1.

Table 1. Soil characteristics (30 cm depth) of the experimental site.

Humus Content (%)	1.4
Soil N_t (%)	0.064
pH ($CaCl_2$)	5.8
Available Total P (mg 100 g^{-1}) [1]	18
Available Total K (mg 100 g^{-1}) [1]	22
Available Total Mg (mg 100 g^{-1}) [2]	8

[1] calcium acetate-lactate extraction; [2] calcium chloride extraction.

Before the establishment of the experiment, the soil was prepared with a mouldboard plough to 25 cm depth on 20 September 2014. A secondary tillage was done by a chisel plow (15 cm depth) on 24 April 2015, 21 April 2016, and 21 April 2017, respectively. On the same day that tillage occurred, maize (*Zea mays*, cv. 'Corioli CS') was sown with a row distance of 0.75 m and a planting density of 10 plants m^{-2}. Each plot consisted of eight rows of maize with a length of 10 m (Figure 2). The row orientation was east-west. The shading treatments (Figure 2, explained later in detail) were randomized in three complete blocks. The harvest was performed at the dough stage on 7 September 2015, 24 August 2016, and 24 August 2017 with a plot harvester (type 'BAURAL SF 2000', Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany, cutting width = 1.50 m). The trial did not consist of repeated measurements. The plots rotated each year into a new strip with winter-sown barley as the previous crop.

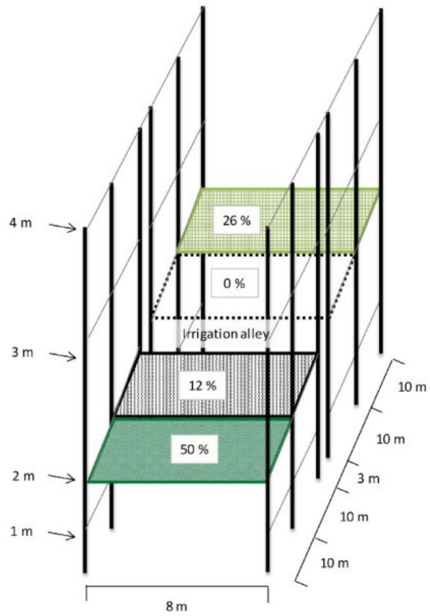


Figure 2. Construction outlines of the artificial shading system in East-to-West-View, exemplarily shown for one repetition. In this example, the nets are installed at a height of 2 m. The numbers in the boxes are the reduction values of solar radiation. The 2nd (12%) and the 3rd (0%) plot were separated by an irrigation alley of 3 m width.

Fertilization and plant protection were done according to the guidelines of Best Agricultural Practices. Fertilizer was applied as ALZON (46% N) at a rate of 151.8 kg N ha^{-1} in 2015, 142.6 kg N ha^{-1} in 2016, and 179.4 kg N ha^{-1} in 2017. In 2015, plant protection comprised of 1.5 L ha^{-1} Clio Super (32 g L^{-1} *topramezone* and 538 g L^{-1} *dimethenamid-p*, BASF SE) applied on 13 May 2015 and, due to strong weed infestation, a mixture of 1 L ha^{-1} Dash EC (345 g L^{-1} *FAME*, 205 g L^{-1} *fatty alcohol alkoxylates*, 46 g L^{-1} *oleic acid*, BASF SE) and 200 g ha^{-1} Arrat (250 g kg^{-1} *tritosulfuron*, 500 g kg^{-1} *dicamba*, BASF SE), which was applied on 15 June 2015. In 2016, a mixture of 0.75 L ha^{-1} Motivell forte (60 g L^{-1} *nicosulfuron*, Belchim Crop Protection NV/SA), 1.4 L ha^{-1} Spectrum (720 g L^{-1} *dimethenamid-p*, BASF SE), and 2 L ha^{-1} Laudis (44 g L^{-1} *tembotrione*, 22 g L^{-1} *isoxadifen-ethyl*, Bayer SE) was applied on 20 May 2016. A mixture of 1.25 L ha^{-1} MaisTer Power (30 g L^{-1} *foramsulfuron*, 9.77 g L^{-1} *thiencarbazone*, 0.85 g L^{-1} *iodosulfuron*, 15 g L^{-1} *cyprosulfamide*, Bayer SE) and 1.25 L ha^{-1} Spectrum was applied on 29 May 2017. Additionally, applications of *Ichneumonidae* spp. (*Trichogramma brassicae* Latreille) were utilized on 19 June 2015, 7 July 2015, 29 June 2016, 14 July 2016, 16 June 2017, and 30 June 2017 as protection against the European corn borer (*Ostrinia nubilalis* Hübner).

During the growing season, all plots were irrigated based on the 'Agrowetter' irrigation device to prevent water stress [41]. Irrigation was done by an irrigation gun at a rate of 30 mm at each irrigation event (29 May 2015, 29 June 2015, 7 July 2015, 16 July 2015, 3 August 2015, 7 July 2016, 13 July 2016, 29 July 2016, 12 August 2016, 31 May 2017, 20 June 2017, and 4 July 2017).

2.2. Shade Levels

Shading was realized by nets, which were stretched between wooden posts linked by steel wires (Figure 2). The relevant characteristics of the shading nets are given in Table 2. These nets reduced the incoming radiation by 12%, 26%, and 50%, respectively. These quantities of light reduction were chosen based on measurements in distances of 4.5, 7.5, and 11 m to the trunk of an 11-year old cherry tree, which was pruned up to 4 m. The control measurements were done at a distance of 20 m from the trunk corresponding to open-field conditions [42]. The height of the shading nets was adapted with increasing plant height to keep the distance between nets and plant canopy during the growing period at 0.5 m. The nets were installed after sowing and removed at harvest. From sowing to harvest, the average incoming solar radiation was 19.96 MJ m^{-2} day^{-1} in 2015, 19.11 MJ m^{-2} day^{-1} in 2016, and 19.73 MJ m^{-2} day^{-1} in 2017. In comparison, the incoming solar radiation below the shading nets was reduced to 17.56 (12%), 14.77 (26%), and 9.98 MJ m^{-2} day^{-1} (50%) in 2015, 16.82 (12%), 14.14 (26%), and 9.56 MJ m^{-2} day^{-1} (50%) in 2016, and 17.36 (12%), 14.60 (26%), and 9.87 MJ m^{-2} day^{-1} (50%) in 2017, respectively.

Table 2. Characteristics of the nets used for light reduction.

	Light Reduction (%)		
	12	**26**	**50**
Manufacturer	AGROFLOR Kunststoff GmbH, Wolfurt, Austria		
Color	black	green	green
Material	polyethylene	polyethylene	polyethylene
Mesh Size (mm)	3 × 8	12 × 12	3 × 3
Original Use	hail protection net	anti-bird net	shade sheet

2.3. Data Collection

2.3.1. Plant Growth

Non-destructive plant growth measurements were only conducted in 2016 and 2017 on six plants located in rows three and six of the plots. These measurements were done two times per week from the 3rd-leaf stage until two weeks after silking (8.5 total weeks in 2016 and 8 total weeks in 2017). From each plant, the growth stage (GS) was determined according to the BBCH scale [43]. Then, canopy height (soil surface to leaf tip or later tip of tassel) was measured. The number of senescent leaves was counted. A leaf was counted senescent when less than 50% was green. Leaf length and maximum width (at the widest part of the leaf) of every fully unrolled leaf were determined. Leaf area (LA) was calculated by the technique of Mokhtarpour et al. [44] using the following Equation:

$$\mathbf{LA = leaf\ length \times leaf\ width \times 0.75} \tag{1}$$

The leaf area index (LAI) was calculated by summing up the area of all leaves of one plant multiplied by the plant density.

2.3.2. Yield

Yield and quality measurements were done in all three growing seasons. At harvest all plants of the two center rows—leaving three border rows on each site—were cut by a crop chopper. The determination of dry matter yield (DMY) and dry substance (DS) were done gravimetrically after oven drying 2 kg of fresh material at 105 °C for two days.

2.3.3. Chemical Analysis and Calculation of Biogas and Methane Yield

For chemical analysis in all three years, an additional 2 kg of the harvested material was dried at 60 °C for two days and milled to 1 mm. Then, P, K, Ca, Mg and S were determined by spectrometry [45–47]. The determination of crude protein (XP), crude fiber (XF), ether extracts (EE), crude ash (XA), and nitrogen-free extractives (NfE) was done according to the Weender analysis [45,48]. With the results of the Weender analysis, the digestibility values of EE, XP, XF, and NfE of fresh maize silage and the DMY, the theoretical yields of biogas and methane were calculated by the Schattauer & Weiland technique [49,50]. For simplification and direct comparability whether the DMY or the quality of the DMY have a greater impact on biogas and methane yield, the formulas have been simplified to the multiplication of DMY with the conversion factors for biogas and methane (C_{biogas} and $C_{methane}$) in Equation (2) and (3). The equations can be found in detail in Schattauer & Weiland [50].

$$\mathbf{Biogas\ yield\ [m^3\ ha^{-1}] = DMY \times C_{biogas}} \tag{2}$$

$$\mathbf{Methane\ yield\ [m^3\ ha^{-1}] = DMY \times C_{methane}} \tag{3}$$

2.4. Data Analysis

The experimental design was a randomized complete block design with three replicates. For the annual analysis of growth data, statistical analysis was done using the PROC MIXED procedure of the SAS system. The fitted model was as follows:

$$y_{ij} = \mu + r_i + s_j + (rs)_{ij} + e_{ij}$$

where y_{ij} is the response, μ the general effect, r_i is the fixed effect of the i-th replicate, s_j is the fixed effect of the j-th shading level, rs_{ij} is the random plot effect where the j-th shading level is used in the i-th replicate, and e_{ij} is the residual error of y_{ij} which corresponds to the plant effect. After finding significant differences via F-test, differences between treatments were compared at $p < 0.05$ using Fisher's LSD test. For creating the letter displays the method of Piepho [51,52] was used.

For multi-year analysis of yield and quality data, an analysis was done using Residual Maximum Likelihood of the PROC MIXED procedure of the SAS system to fit a linear mixed model. The fitted model was:

$$y_{ijl} = \mu + a_l + s_j + (ra)_{il} + (as)_{lj} + e_{ijl}$$

where y_{ijl} is the response, μ the general effect, a_l is the effect of the l-th year, s_j is the fixed effect of the j-th shading level, ra_{il} is the effect of the i-th replicate in the l-th year, as_{lj} is the random interaction effect between the l-th year and the j-th shading level, and e_{ijl} is the residual error of y_{ijl}. If necessary, meaning if the AIC decreases, year-specific error variances were fitted.

Note that year (and replicate) effects are assumed as random, but the main effects were treated as fixed in the model because only three-year data (with nine replicates) were analyzed [53]. Furthermore, for balanced data as it is the case for the data in this study, no inter-year (and inter-replicate) information exists, thus models assuming random and fixed effects results in identical relevant results [53].

The variance of year effect is normally large. So, we assume year as random effect. Otherwise the variance component for the small number of years had to be estimated. However, this is only possible with more than 10 degrees of freedom, for which there should be more than four replications [53]. To make sure that no information is weighted incorrectly, the year is set as fixed effect in the model.

Again, after finding significant differences via F-test, differences between treatments were compared at $p < 0.05$ using Fisher's LSD test. For both models, normality and homogeneous variances were checked graphically.

3. Results

3.1. Growth Stages

No differences in emergence date were observed for maize plants grown at different shading levels in 2016 and 2017. Emergence took place 18 and 23 days after sowing, respectively (DAS, Table 3). In 2016 tassel initiation was observed after 74 DAS in the control and the 12% shading treatment. Fifty percent shading led to a delay of 11 days compared to the control. Increasing the shading to 50% further delayed silking to about 9 days to a total of 90 DAS. The end of flowering was delayed for only two days (99 DAS vs. 97 DAS) under 50% shade when compared to the control and the 12% shading treatment. Dough stage (harvest) was reached in the control after 126 DAS. Increasing shade to 50% delayed the dough stage about 7 days. In 2017, between the control and the 50% shade, there was a delay of 11 days in silking. The end of flowering was observed 91 DAS at 50% shade. The other three treatments reached this stage at 87 DAS. There was a difference of 16 days between the control and 50% shade reaching the dough stage.

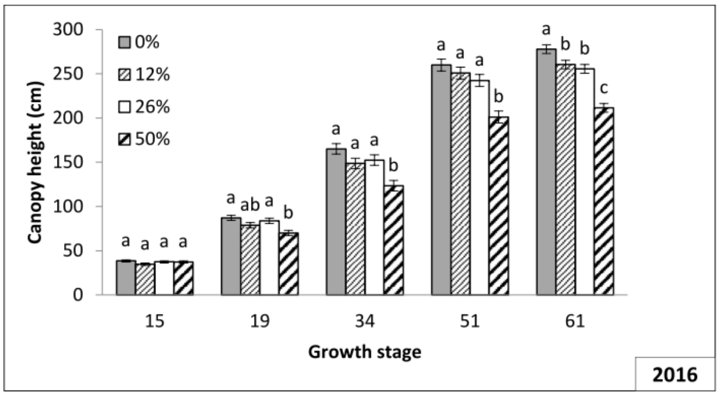
Table 3. Days after sowing (DAS) until the growing stages (GS) emergence (GS 09), tassel initiation (GS 51), silking (GS 61), end of flowering (GS 69), and dough stage (GS 85) under different shading levels (0, 12, 26, and 50%) in 2016 and 2017 and the standard error of means (SEM).

Year	Shade	Emergence †		Tassel Initiation		Silking		End of Flowering †		Dough Stage	
2016	**0%**	18	(±0.00)	74 a	(±0.33)	81 a	(±0.71)	97 a	(±0.22)	126 ab	(±1.67)
	12%	18	(±0.00)	74 a	(±0.33)	84 ab	(±0.71)	97 a	(±0.22)	123 a	(±1.67)
	26%	18	(±0.00)	80 b	(±0.33)	85 b	(±0.71)	98 a	(±0.22)	133 b	(±1.67)
	50%	18	(±0.00)	81 b	(±0.33)	90 c	(±0.71)	99 b	(±0.22)	133 b	(±1.67)
2017	**0%**	23	(±0.00)	67 a	(±0.33)	71 a	(±0.40)	87 a	(±0.00)	110 a	(±2.05)
	12%	23	(±0.00)	68 a	(±0.33)	73 b	(±0.40)	87 a	(±0.00)	112 a	(±2.05)
	26%	23	(±0.00)	73 b	(±0.33)	77 c	(±0.40)	87 a	(±0.00)	117 ab	(±2.05)
	50%	23	(±0.00)	76 c	(±0.33)	82 d	(±0.40)	91 b	(±0.00)	126 b	(±2.05)

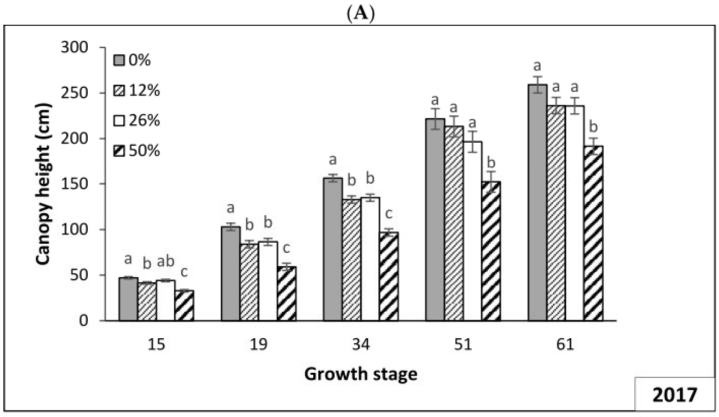
Standard errors of means are given in parentheses. Means with identical letters within each column and year show non-significant differences between the shade levels of the single years (LSD, $p < 0.05$). † Note: The SEM was between 0 and 0.005, so rounding to two decimal places resulted in a SEM of zero.

3.2. Plant Growth

Canopy height was reduced by shading, which was especially pronounced at 50% shade during the growing seasons in 2016 and 2017 (Figure 3). In 2016, there was a strong reduction in the maximum canopy height (−24%) under 50% shade with a maximum canopy height of 212 cm compared to the control with 278 cm. Canopy heights under 12% and 26% shade showed only slight differences between each other and were significantly lower than the control with maximum canopy heights of 260 and 256 cm at GS 61, respectively. In 2017, final height under 50% shade was 192 cm, corresponding to a reduction of 26% compared to the control. Under 12 and 26% shade, final canopy heights did not differ significantly from the control.



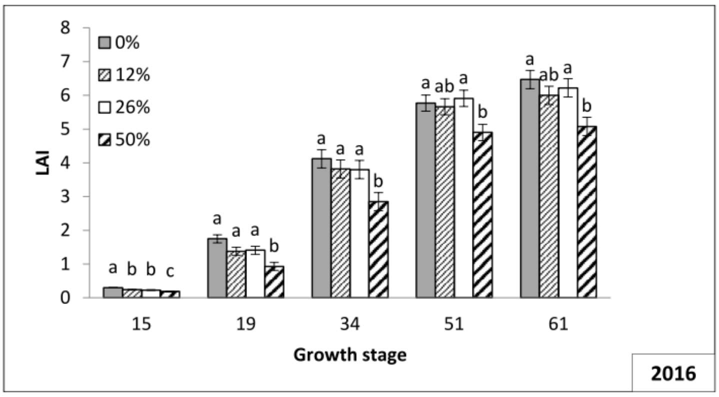
(A)



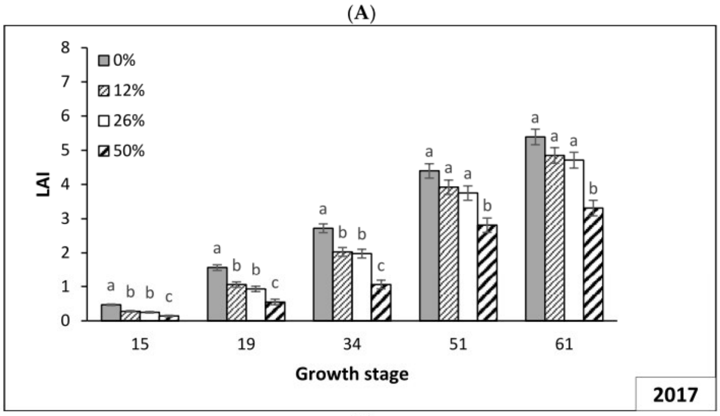
(B)

Figure 3. Canopy height (cm) under the different shading levels at the growth stages 15 (5th leaf unfolded), 19 (9th or more leave unfolded), 34 (4 nodes detectable), 51 (tassel initiation), and 61 (silking) of the control in 2016 (**A**) and 2017 (**B**). Black bars represent the standard error of mean. Means with identical letters within a growth stage show non-significant differences between the shade levels (LSD, $p < 0.05$).

In 2016 and 2017, the LAI was significantly reduced under 50% shade at all growth stages until silking compared to the control (Figure 4). The maximum LAI was reduced by 21% and 39% in 2016 and 2017, respectively. Under 12% and 26% shade, the maximum LAI did not differ from each other and was only slightly lower than the control at early growth stages in both years.



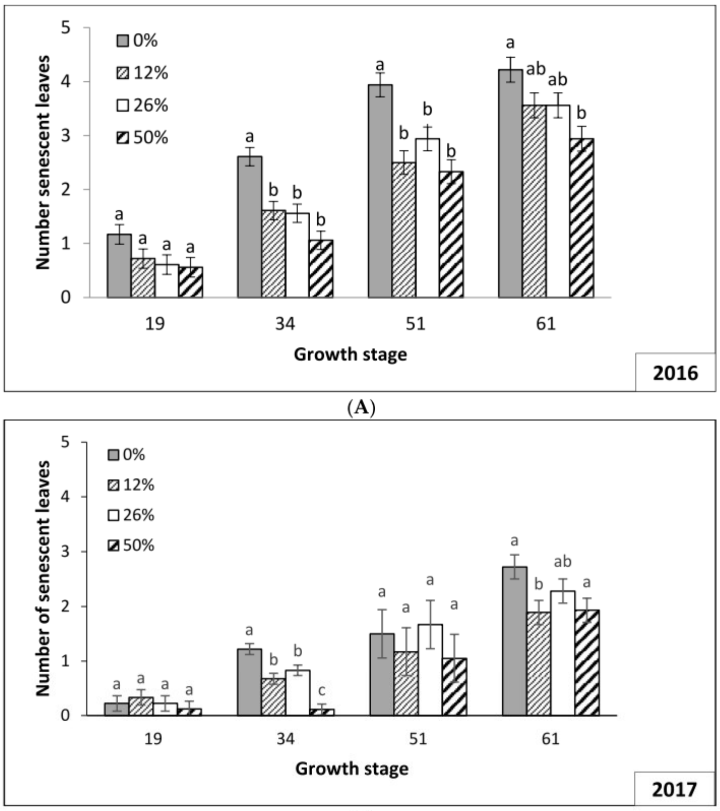
(**A**)



(**B**)

Figure 4. LAI under the different shading levels at the growth stages 15 (5th leaf unfolded), 19 (9th or more leave unfolded), 34 (4 nodes detectable), 51 (tassel initiation), and 61 (silking) of the control in 2016 (**A**) and 2017 (**B**). Black bars represent the standard error of mean. Means with identical letters within a growth stage show non-significant differences between the shade levels (LSD, $p < 0.05$).

Leaf senescence was first observed when the control reached the 8th-leaf stage. In both years, shading delayed senescence from GS 34 onwards (Figure 5). In general, the control had around one senescent leaf more than under 50% shade. In 2017, this effect was less pronounced and high standard errors did not lead to significant differences at GS 51. The high standard errors occurred from the fact, that some of the six observed plants of one plot already did not have any senescent leaf at this time, while other plants in the same plot already had three senescent leaves.



(B)

Figure 5. Number of senescent leaves per plant under the different shading levels at the growth stages 15 (5th leaf unfolded), 19 (9th or more leave unfolded), 34 (4 nodes detectable), 51 (tassel initiation), and 61 (silking) of the control in 2016 (**A**) and 2017 (**B**). Black bars represent the standard error of mean. Means with identical letters within a growth stage show non-significant differences between the shade levels (LSD, $p < 0.05$).

3.3. Yield and Quality

There were significant differences between biomass yield as well as the quality parameters and biogas and methane yields at different shade levels (Table 4).

DMY decreased with increasing shade. The mean yield of the control across the three experimental years was 21.05 Mg DM ha^{-1} year^{-1}. The DMY under 12% and 26% was significantly different from the control and the 50% shade, but not from each other. Compared to the control, DMY was 18% and 19% lower under 12% and 26% shade, respectively. The 50% shade resulted in a significantly lower DMY compared to all other treatments, with a reduction of 44% compared to the control.

DS also decreased with increasing light reduction from 39.48% in the control to 32.23% under 50% shade. XP showed a significant increase with increasing shade up to 7.16% in the 50% shade treatment compared to 6.04% of the control. The 12% and 26% shade resulted in an XP content of 6.42% and 6.63%, respectively and did not differ from the control. No significant differences were observed for XF, EE and NfE.

Table 4. Means for DMY (Dry Matter Yield, Mg ha^{-1} year^{-1}), DS (Dry Substance, %), biogas, and methane quality parameters (XP, XF, EE, XA and NfE) (% of dry matter), conversion factor C_{biogas} and $C_{methane}$ and theoretical biogas- and methane yield (m^3 ha^{-1}) for the different shade levels (0%, 12%, 26%, and 50%) over the three experimental years (2015–2017).

Constituent	Shade Level								*p*-Value	LSD
	0%		12%		26%		50%			
DMY	21.05 a	(±0.53)	17.24 b	(±0.53)	17.08 b	(±0.53)	11.73 c	(±0.53)	<0.001	1.54
DS	39.48 a	(±0.71)	36.39 b	(±0.71)	35.98 b	(±0.71)	32.23 c	(±0.71)	<0.001	2.07
XP	6.04 a	(±0.20)	6.42 ab	(±0.20)	6.63 bc	(±0.20)	7.16 c	(±0.20)	0.008	0.58
XF	19.50	(±0.87)	19.52	(±0.87)	19.09	(±0.87)	19.12	(±0.87)	0.973	3.01
EE	2.84	(±0.19)	2.76	(±0.19)	2.99	(±0.19)	3.02	(±0.19)	0.721	0.65
XA	3.01 a	(±0.09)	3.32 ab	(±0.09)	3.45 b	(±0.09)	3.98 c	(±0.09)	0.002	0.31
NfE	68.72	(±1.05)	68.01	(±1.05)	67.87	(±1.05)	66.55	(±1.05)	0.565	3.64
$\mathbf{C_{biogas}}$	54.41	(±0.17)	54.12	(±0.17)	54.10	(±0.17)	53.65	(±0.17)	0.096	0.59
$\mathbf{C_{methane}}$	29.39	(±0.09)	29.25	(±0.09)	29.29	(±0.09)	29.12	(±0.09)	0.267	0.30
Biogas	11,455 a	(±280)	9315 b	(±280)	9241 b	(±280)	6321 c	(±280)	<0.001	819
Methane	6188 a	(±150)	5038 b	(±150)	4999 b	(±150)	3437 c	(±150)	<0.001	436

Standard errors of means (SEM) are given in parentheses. Means with identical letters within a shade level show non-significant differences between the shade levels (LSD, $p < 0.05$).

The content of XA increased with increasing shade up to 3.98% under 50% shade corresponding to an increase of 32% compared to the control. Under 26% shade, the XA content differed significantly from the control and 50% shade with an increase of 15% compared to the control.

The conversion factor for biogas C_{biogas} decreased insignificantly, with increasing shade from 54.41% in the control to 53.65% under 50% shade. As a result, together with the decreased DMY, the theoretical biogas yield decreased by 45% from 114,855 m^3 ha^{-1} in the control to 6321 m^3 ha^{-1} at 50% shade. The lower shading levels (12% and 26%) did not differ significantly from each other but were significantly lower than the control with around 9300 m^3 ha^{-1}. The $C_{methane}$ showed no significant differences between the tested shading treatments. The reduction of the value was for all shading treatments under 1%. But in combination with the decreased DMY the theoretical methane yield was reduced about 45% under 50% shade compared to the control, which was similar to the reduction of biogas yield. Both under 12% and 26% shade, the methane yield was 19% lower than the control.

3.4. Macronutrients

The content of the macronutrients P, K, Ca, Mg, and S showed an increase with increasing shade (Table 5). Across the three years, phosphorus and potassium had the largest increase up to 37%. The increase of the other macronutrients was in a range of 10 to 25% from the control to 50% shade. Shading had no significant effect on the calcium, magnesium and sulfur content.

Table 5. Average content of macronutrients (% of dry matter) phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) for the different shade levels (0%, 12%, 26%, and 50%) over the three experimental years (2015–2017).

Constituent	Shade Level								*p*-Value	LSD
	0%		12%		26%		50%			
P	0.11 a	(±0.01)	0.13 ab	(±0.01)	0.13 b	(±0.01)	0.15 c	(±0.01)	0.003	0.03
K	0.98 a	(±0.04)	0.98 a	(±0.04)	1.12 a	(±0.04)	1.34 b	(±0.04)	0.003	0.15
Ca	0.09	(±0.01)	0.09	(±0.01)	0.10	(±0.01)	0.11	(±0.01)	0.348	0.03
Mg	0.08	(±0.00)	0.09	(±0.00)	0.09	(±0.00)	0.10	(±0.00)	0.105	0.01
S	0.10	(±0.00)	0.10	(±0.00)	0.10	(±0.00)	0.11	(±0.00)	0.349	0.01

Standard errors of means (SEM) are given in brackets. Means with identical letters within a shade level show non-significant differences between the shade levels (LSD, $p < 0.05$).

4. Discussion

In order to counteract the potential negative environmental effects of large maize monocropping areas for biogas production, the cultivation of maize in intercropping systems or AFS is considered as a possible alternative. However, especially in an AFS the maize plant is experiencing competition for light, nutrients and water. It is expected that this competition will impact final biomass and quality of the maize plant and thus overall formation of biogas and methane.

In our study, shading significantly influenced plant development by delaying the occurrence of growing stages as well as senescence. These results are in line with other studies showing delayed development of maize shaded by earlier sown winter wheat in an intercropping system and delayed senescence of winter wheat under 12% of shade [54,55]. Even though the vegetative period of maize was longer under shade, the final plant height and LAI were considerably lower, indicating that plant growth was strongly suppressed by shading.

Finally, changes in height and LAI caused biomass yield to be largely reduced [56–59]. The delayed senescence, in turn, resulted in a lower DS under shade. However, in all treatments, DS of the harvested maize was in the recommended range of 30%–40% for ensiling [60] and, thus, can reach maximum biogas yields [29]. Reynolds et al. [16] observed in an AFS of poplar (*Populus* spp. L.) and maple trees (*Acer* spp. L.) intercropped with maize a significant height reduction of maize plants. The maize height in the poplar intercropping systems was reduced to about 41% in 2 m distance to tree trunk compared to the maize height in 6 m distance. For maple trees, the reduction at the same distances was 37%. Maize genotypes which showed to be intolerant in their growth to low light intensities were intercropped with oil palms and showed a lower plant height under shading levels of 22, 37, and 76% [22].

These reductions were attributed to the changed light conditions and, thus, reduced photosynthesis rates. Maize is known as a shade-intolerant C_4 species. By reducing its photosynthesis under shade, the electron transport and the carboxylation enzymes are reduced in the photosynthetic apparatus [26]. This was shown in a trial with maize/walnut and maize/plum intercropping. In 1 m distance from tree trunk, the plant height was reduced by about 16% and 20%, respectively. The reduction in height was attributed to the reduced photosynthesis rates. As a result, plants had less energy available for growth processes. LAI, as the second major biomass forming parameter, showed the same trend. A shading of 50% resulted in a significantly reduced LAI. Allison and Daynard [61] observed a 20% decrease in leaf area per plant if the time to silking is changed. This is in line with our observed results were a shade-induced prolonged interval of 2 to 9 days from emergence to start of flowering reduced final LAI by 22% and 39%, respectively. Other studies also showed a reduced leaf area under changes in the light environment. Dadashi et al. [62] observed in a weedy plant stand that this reduction was attributed to the reduced plant available light. As a result, the photosynthesis was also reduced, which resulted in lower plant growth.

Dadashi et al. [62] also found that the rates of accumulation of dry matter and leaf area were reduced by stress. Hence, a delayed occurrence of the phenological phases leads to a shorter period of biomass accumulation and, thus, a reduction in the final biomass yield, if harvest is timed on the ripeness of plants in non-shaded field sections. Sinclair and Horie [63] showed that the more LAI is available, the higher the radiation use efficiency is. The potential of a crop to accumulate biomass could be described by a function of the accumulated amount of biomass per unit of solar radiation. Dry matter accumulation rate varied in direct proportion to the amount of intercepted radiation. A shortening of the flowering phase negatively affected the leaf area and, also, on photosynthesis, which causes a reduced biomass growth and dry matter yield.

Our study showed that maize only showed a significant reduction in height and LAI at 50% shade. However, DS was significantly decreased even in the 12% shade treatment. Hence, the combination of growth parameters and DS resulted in a significantly reduced DMY even in the 12% shading treatment.

In addition to the amount of biomass produced, the quality-determining compounds also influence final biogas and methane yield. Results of our study indicated that only XP and XA were significantly influenced by shading. A significant increase in XP occurred at 50% shade, while XA significantly increased in the 12% shading treatment. The other quality determining parameters (XF, EE, NfE) showed no significant change under shading.

XP is an important component for biogas and methane formation in a biogas plant. A high amount of XP leads to a higher concentration of methane in biogas [64,65]. The results of our study were similar to the outcomes of Lin et al. [66] and showed an increasing protein content with increased shade intensity. Under 26% shade there was an increase in XP of 11%. Protein content increased due to an overall reduction in biomass yields. The same amount of nitrogen was available, but less biomass was built. An intercropping trial of loblolly pine trees (*Pinus taeda* L.) with herbages in a silvopastoral AFS in the southeastern USA showed at a shade of 55% that the plants XP of 11.5% was higher, compared to XP of 8.5% at 0% shade [67]. If less yield is formed, available nitrogen is less diluted and accumulates in higher concentrations of XP in these biomasses [33]. As shown by Early et al. [30], an increased protein content of vegetative plant parts grown under shade is associated with a reduction in plant growth and a decrease in kernel production.

XA showed a 10% increase under 12% shade, while under 50% shade there was an increase of 32%. High XA contents can be problematic in the biogas process, as XA is not degradable by the biogas microorganisms. If the XA content is too high, the ash can settle on the bottom of the fermenter and reduce the digestion space. This reduction can disturb and inhibit the biogas process. Maturation of plants is responsible for the number of digestible components. Within the progress of maturity, the proportion of inorganic matter decreases. Since the shaded plants were delayed in maturity, they showed a higher level of inorganic matter or XA [68,69]. We observed a shade-induced prolonged development and, thus, a delayed maturity, which caused higher XA contents.

All tested minerals, except Ca and S, showed a steady increase with shading intensity. However, increases in P, K, Mg were in an acceptable range that would not have a tremendous effect on the biogas formation process [37,38,40,70,71].

If we assume a density of 200 kg m^{-3} for maize silage dry matter, the critical values would be 1.5% for potassium, 0.5% for calcium, 0.3% for magnesium, and 1.9%–4.7% for sulfur [40,70]. If we convert the determined macronutrient contents of the 50% shade treatment on a DS base, values of 0.43% (potassium), 0.04% (calcium), 0.03% (magnesium), and 0.04% (sulfur) would be achieved. Hence, no negative impact on the biogas formation would be expected.

Biogas is a mixture with major proportions of methane (40%–75%) and carbon dioxide (25%–55%), as well as other gases in very low concentrations. Methane has a high energy content, which makes it a valuable compound of the overall biogas composition. In literature, there is no information available on how biogas and methane yield are influenced under different light reductions. Overall, the increase of non-degradable XA and the increase of slowly degradable XP in combination with the reduced biomass yields led to lower biogas and methane yields. Even under 12 % shading, biogas and methane yields were significantly reduced by up to 19%, due to lower biomass yields. A shading of 50% led to almost half of the final biomass and biogas and methane yields.

From yield aspects, silage maize cannot be recommended for the shade conditions in an AFS if compared to monocropping. But even with a shading of 26%, the maize has higher methane yields than cereal monocropping for biogas purpose, which generates 3200 to 4500 m^3 ha^{-1} methane [3]. If the below-ground factors, like nutrient, water and soil fauna are disregarded and the system is only considered for its light competition, silage maize cultivation up to a shading level of 26% can be possible. If political support for AFS in Germany would be granted, as it is already the case in France, silage maize production in an AFS could be profitable for the farmer [13]. However, further studies on the effect of the below-ground interactions would be needed to assess the system as a whole.

5. Conclusions

In all tested shading treatments, final biomass yield was reduced. The results indicated that shading maize at a level of 50% reduced the dry matter biomass yields up to nearly 50%. In addition, contents of XP and XA increased at a shading level of 50% and 12%, respectively. Other biogas parameters were not influenced by shade. Biogas and methane yield were also reduced at 12% shading. Overall, results of our study suggest that shading up to 26% would be tolerable for maize if the positive contribution of the tree strips is also taken into account. However, further investigations on the below-ground interactions are necessary to fully understand and evaluate these systems.

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References

1. Anonymous 2020 Climate & Energy Package. Available online: https://ec.europa.eu/clima/policies/strategies/2020_en (accessed on 28 October 2017).
2. Fachagentur Nachwachsende Rohstoffe e.V. Basisdaten Nachwachsende Rohstoffe. Available online: https://basisdaten.fnr.de/ (accessed on 28 October 2017).
3. Amon, T.; Amon, B.; Kryvoruchko, V.; Machmüller, A.; Hopfner-Sixt, K.; Bodiroza, V.; Hrbek, R.; Friedel, J.; Pötsch, E.; Wagentristl, H. Others Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresour. Technol.* **2007**, *98*, 3204–3212. [CrossRef] [PubMed]
4. Varah, A.; Jones, H.; Smith, J.; Potts, S.G. Enhanced biodiversity and pollination in UK agroforestry systems. *J. Sci. Food Agric.* **2013**, *93*, 2073–2075. [CrossRef] [PubMed]
5. Vandermeer, J.H. *The Ecology of Intercropping*; Cambridge University Press: New York, NY, USA, 1992.
6. Montagnini, F.; Nair, P.K.R. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.* **2004**, *61*, 281–295. [CrossRef]
7. Rigueiro-Rodríguez, A.; Fernández-Núñez, E.; González-Hernández, P.; McAdam, J.H.; Mosquera-Losada, M.R. Agroforestry Systems in Europe: Productive, Ecological and Social Perspectives. In *Agroforestry in Europe*; Springer: Dodrecht, The Netherlands, 2009; pp. 43–65.
8. Quinkenstein, A.; Böhm, C.; Freese, D.; Wöllecke, J.; Grünewald, H.; Schneider, B.U.; Hüttl, R.F.; GeoForschungsZentrum, H.-Z.P.D. Alley-Cropping-Ein klima-adaptierbares landnutzungssystem zur nachhaltigen Biomasseproduktion. *Forum Forsch.* **2008**, *21*, 131–138.
9. Nii-Annang, S.; Grünewald, H.; Freese, D.; Hüttl, R.F.; Dilly, O. Microbial activity, organic C accumulation and ^{13}C abundance in soils under alley cropping systems after 9 years of recultivation of quaternary deposits. *Biol. Fertil. Soils* **2009**, *45*, 531–538. [CrossRef]
10. Rivest, D.; Cogliastro, A.; Bradley, R.L.; Olivier, A. Intercropping hybrid poplar with soybean increases soil microbial biomass, mineral N supply and tree growth. *Agrofor. Syst.* **2010**, *80*, 33–40. [CrossRef]
11. Chauhan, S.K.; Sharma, R.; Sharma, S.C.; Gupta, N. Evaluation of poplar (*Populus deltoides* Bartr. Ex Marsh.) boundary plantation based agri-silvicultural system for wheat-paddy yield and carbon storage. *Int. J. Agric. For.* **2012**, *2*, 239–246.
12. Lamerre, J.; Schwarz, K.-U.; Langhof, M.; von Wühlisch, G.; Greef, J.-M. Productivity of poplar short rotation coppice in an alley-cropping agroforestry system. *Agrofor. Syst.* **2015**, *89*, 933–942. [CrossRef]
13. Dupraz, C. Prospects for easing land tenure conflicts with agroforestry in Mediterranean France: A research approach for intercropped timber orchards. *Agrofor. Syst.* **1994**, *25*, 181–192. [CrossRef]
14. Nissen, T.M.; Midmore, D.J. Stand basal area as an index of tree competitiveness in timber intercropping. *Agrofor. Syst.* **2002**, *54*, 51–60. [CrossRef]

15. Peichl, M.; Thevathasan, N.V.; Gordon, A.M.; Huss, J.; Abohassan, R.A. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. *Agrofor. Syst.* **2006**, *66*, 243–257. [CrossRef]
16. Reynolds, P.E.; Simpson, J.A.; Thevathasan, N.V.; Gordon, A.M. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. *Ecol. Eng.* **2007**, *29*, 362–371. [CrossRef]
17. Bertomeu, M. Growth and yield of maize and timber trees in smallholder agroforestry systems in Claveria, Northern Mindanao, Philippines. *Agrofor. Syst.* **2012**, *84*, 73–87. [CrossRef]
18. Ong, C.K.; Corlett, J.E.; Singh, R.P.; Black, C.R. Above and below ground interactions in agroforestry systems. *For. Ecol. Manag.* **1991**, *45*, 45–57. [CrossRef]
19. Smith, J.; Pearce, B.D.; Wolfe, M.S. Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renew. Agric. Food Syst.* **2013**, *28*, 80–92. [CrossRef]
20. Chen, T.; Song, Z.; Zhang, M.; Yan, X.; Zhu, P.; Ren, Y.; Deng, A.; Zhang, W. Effects of shading and planting density on ear development and plant productivity of spring maize in Northeast China. *Chin. J. Appl. Ecol.* **2016**, *27*, 3237–3246.
21. Early, E.B.; McIlrath, W.O.; Seif, R.D.; Hageman, R.H. Effects of Shade Applied at Different Stages of Plant Development on Corn (*Zea mays* L.) Production 1. *Crop. Sci.* **1967**, *7*, 151–156. [CrossRef]
22. Syafrullah; Marlina, N.; Rahim, S.E.; Aminah, R.I.S.; Midranisiah; Rosmiah; Sakalena, F. Growth and Production of Some Variety Corn (*Zea mays* L.). Planted under the Canopy of Palm Oil 12 Years Old in Swamp Land. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Iasi, Romania, 2017; Volume 209, p. 012109.
23. Maddonni, G.A.; Otegui, M.E.; Cirilo, A.G. Plant population density, row spacing and hybrid effects on maize canopy architecture and light attenuation. *Field Crops Res.* **2001**, *71*, 183–193. [CrossRef]
24. Tiwari, T.P.; Brook, R.M.; Wagstaff, P.; Sinclair, F.L. Effects of light environment on maize in hillside agroforestry systems of Nepal. *Food Secur.* **2012**, *4*, 103–114. [CrossRef]
25. Singh, S. Physiological response of different crop species to low light stress. *Indian J. Plant Physiol.* **1994**, *37*, 147–151.
26. Peng, X.; Zhang, Y.; Cai, J.; Jiang, Z.; Zhang, S. Photosynthesis, growth and yield of soybean and maize in a tree-based agroforestry intercropping system on the Loess Plateau. *Agrofor. Syst.* **2009**, *76*, 569–577. [CrossRef]
27. Baserga, U. *Landwirtschaftliche Co-Vergärungs-Biogasanlagen: Biogas aus organishcen Reststoffen und Energiegras*; FAT-Berichte: Tänikon, Switzerland, 1998.
28. Jia, S.-F.; Li, C.-F.; Dong, S.-T.; Zhang, J.-W. Effects of shading at different stages after anthesis on maize grain weight and quality at cytology level. *Agric. Sci. China* **2011**, *10*, 58–69. [CrossRef]
29. Amon, T.; Amon, B.; Kryvoruchko, V.; Zollitsch, W.; Mayer, K.; Gruber, L. Biogas production from maize and dairy cattle manure—Influence of biomass composition on the methane yield. *Agric. Ecosyst. Environ.* **2007**, *118*, 173–182. [CrossRef]
30. Earley, E.B.; Miller, R.J.; Reichert, G.L.; Hageman, R.H.; Seif, R.D. Effect of shade on maize production under field conditions. *Crop. Sci.* **1966**, *6*, 1–7. [CrossRef]
31. Proulx, R.A.; Naeve, S.L. Pod removal, shade, and defoliation effects on soybean yield, protein, and oil. *Agron. J.* **2009**, *101*, 971–978. [CrossRef]
32. Kryvoruchko, V.; Machmüller, A.; Bodiroza, V.; Amon, B.; Amon, T. Anaerobic digestion of by-products of sugar beet and starch potato processing. *Biomass Bioenergy* **2009**, *33*, 620–627. [CrossRef]
33. McEwen, L.C.; Dietz, D.R. Shade effects on chemical composition of herbage in the Black Hills. *J. Range Manag.* **1965**, 184–190. [CrossRef]
34. Steffen, F.; Requejo, A.; Ewald, C.; Janzon, R.; Saake, B. Anaerobic digestion of fines from recovered paper processing–Influence of fiber source, lignin and ash content on biogas potential. *Bioresour. Technol.* **2016**, *200*, 506–513. [CrossRef] [PubMed]
35. Zhao, D.; Oosterhuis, D.M. Influence of shade on mineral nutrient status of field-grown cotton. *J. Plant Nutr.* **1998**, *21*, 1681–1695. [CrossRef]
36. Mayland, H.F.; Grunes, D.L. Shade-induced grass-tetany-prone chemical changes in *Agropyron desertorum* and *Elymus cinereus*. *J. Range Manag.* **1974**, 198–201. [CrossRef]

37. Fang, C.; Boe, K.; Angelidaki, I. Anaerobic co-digestion of desugared molasses with cow manure; focusing on sodium and potassium inhibition. *Bioresour. Technol.* **2011**, *102*, 1005–1011. [CrossRef] [PubMed]
38. Ahn, J.-H.; Do, T.H.; Kim, S.D.; Hwang, S. The effect of calcium on the anaerobic digestion treating swine wastewater. *Biochem. Eng. J.* **2006**, *30*, 33–38. [CrossRef]
39. Appari, S.; Janardhanan, V.M.; Bauri, R.; Jayanti, S.; Deutschmann, O. A detailed kinetic model for biogas steam reforming on Ni and catalyst deactivation due to sulfur poisoning. *Appl. Catal. Gen.* **2014**, *471*, 118–125. [CrossRef]
40. Bożym, M.; Florczak, I.; Zdanowska, P.; Wojdalski, J.; Klimkiewicz, M. An analysis of metal concentrations in food wastes for biogas production. *Renew. Energy* **2015**, *77*, 467–472. [CrossRef]
41. Janssen, W. Online Irrigation Service for Fruit and Vegetable Crops at Farmers Site. In Proceedings of the 9th EMS Annual Meeting & 9th European Conference on Applications of Meteorology (ECAM), Toulouse, France, 28 September–2 October 2009; European Meteorological Society: Toulouse, France, 2009.
42. Bender, B. *Moderne Agroforstsysteme mit Werthölzern: Leitfaden für die Praxis*; Bundesministerium für Bildung und Forschung: Reute, Germany, 2009.
43. Hack, H.; Gall, H.; Klemke, T.H.; Klose, R.; Meier, U.; Stauss, R.; Witzenberger, A. The BBCH scale for phenological growth stages of potato (*Solanum tuberosum* L.). In *Proceedings of the 12th Annual Congress of the European Association for Potato Research*; Federal Biological Research Centre for Agriculture and Forestry: Quedlinburg, Germany, 1993; pp. 153–154.
44. Mokhtarpour, H.; Teh, C.B.; Saleh, G.; Selamat, A.B.; Asadi, M.E.; Kamkar, B. Non-destructive estimation of maize leaf area, fresh weight, and dry weight using leaf length and leaf width. *Commun. Biometry Crop. Sci.* **2010**, *5*, 19–26.
45. Bassler, R. *VDLUFA-Methodenbuch, Band III. Die Chemische Untersuchung von Futtermitteln. 3. Aufl., 2. Ergänzungslieferung 1988 und 3. Ergänzungslieferung 1993*; VDLUFA-Verl: Darmstadt, Germany, 1988.
46. Hoffmann, G. *VDLUFA-Methodenbuch Band I: Die Untersuchung von Boeden. Darmstadt, VDLUFA-Verlag, Loseblattsammlung*; Ī. Neumann-Verl. Radebeul u. Berlin 3: Darmstadt, Germany, 1991; ISBN 3-922712-42-8.
47. Janßen, E. *VDLUFA-Methodenbuch, Band VII. Umweltanalytik*, 3rd ed.; VDLUFA: Darmstadt, Germany, 2003.
48. Amtsblatt der Europäischen Union. Verordnung (EG) Nr. 152/2009 der Kommission vom 27.01. 2009 zur Festlegung der Probenahmeverfahren und Analysemethoden für die Amtliche Untersuchung von Futtermitteln. 2009. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:054:0001:0130:DE:PDF (accessed on 20 August 2018).
49. Deutsche Landwirtschafts-Gesellschaft. *DLG-Futterwerttabellen-Wiederkäuer*; DLG-Verlag: Frankfurt am Main, Germany, 1997.
50. Schattauer, A.; Weiland, P. Grundlagen der Anaeroben Fermentation. In *Handreichung Biogasgewinnung und–nutzung*; Herausgeber: Fachagentur Nachwachsende Rohst. e.V.: Gülzow, Germany, 2004; pp. 25–35.
51. Piepho, H.-P. An algorithm for a letter-based representation of all-pairwise comparisons. *J. Comput. Graph. Stat.* **2004**, *13*, 456–466. [CrossRef]
52. Piepho, H.-P. A SAS macro for generating letter displays of pairwise mean comparisons. *Commun. Biometry Crop. Sci.* **2012**, *7*, 4–13.
53. Möhring, J.; Williams, E.; Piepho, H.-P. Inter-block information: To recover or not to recover it? *Theor. Appl. Genet.* **2015**, *8*, 1541–1554. [CrossRef] [PubMed]
54. Zhu, J.; Vos, J.; van der Werf, W.; van der Putten, P.E.; Evers, J.B. Early competition shapes maize whole-plant development in mixed stands. *J. Exp. Bot.* **2013**, *65*, 641–653. [CrossRef] [PubMed]
55. Xu, C.; Tao, H.; Pu, W.; Wang, Z. Slight shading after anthesis increases photosynthetic productivity and grain yield of winter wheat (*Triticum aestivum* L.) due to the delaying of leaf senescence. *J. Integr. Agric.* **2016**, *15*, 63–75. [CrossRef]
56. Gitelson, A.A.; Viña, A.; Arkebauer, T.J.; Rundquist, D.C.; Keydan, G.; Leavitt, B. Remote estimation of leaf area index and green leaf biomass in maize canopies. *Geophys. Res. Lett.* **2003**, *30*, 1248. [CrossRef]
57. Law-Ogbomo, K.E.; Remison, S.U. Growth and Yield of Maize as Influenced by Sowing Date and Poultry Manure Application. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2009**, *37*, 199–203.
58. Gao, S.; Niu, Z.; Huang, N.; Hou, X. Estimating the Leaf Area Index, height and biomass of maize using HJ-1 and RADARSAT-2. *Int. J. Appl. Earth Obs. Geoinf.* **2013**, *24*, 1–8. [CrossRef]

59. Li, W.; Niu, Z.; Chen, H.; Li, D.; Wu, M.; Zhao, W. Remote estimation of canopy height and aboveground biomass of maize using high-resolution stereo images from a low-cost unmanned aerial vehicle system. *Ecol. Indic.* **2016**, *67*, 637–648. [CrossRef]
60. Wiersma, D.W.; Carter, P.R.; Albrecht, K.A.; Coors, J.G. Kernel milkline stage and corn forage yield, quality, and dry matter content. *J. Prod. Agric.* **1993**, *6*, 94–99. [CrossRef]
61. Allison, J.C.S.; Daynard, T.B. Effect of change in time of flowering, induced by altering photoperiod or temperature, on attributes related to yield in maize. *Crop. Sci.* **1979**, *19*, 1–4. [CrossRef]
62. Dadashi, F.; Zaefarian, F.; Abbasi, R.; Bahmanyar, M.A.; Rezvani, M. Response of leaf area and dry matter of crop, weeds and cover crops to competition and fertilizer resources. *Acta Agric. Slov.* **2015**, *103*, 27–36. [CrossRef]
63. Sinclair, T.R.; Horie, T. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop. Sci.* **1989**, *29*, 90–98. [CrossRef]
64. Amon, T.; Amon, B.; Kryvoruchko, V.; Bodiroza, V.; Pötsch, E.; Zollitsch, W. Optimising methane yield from anaerobic digestion of manure: Effects of dairy systems and of glycerine supplementation. In *International Congress Series*; Elsevier: Zurich, Switzerland, 2006; Volume 1293, pp. 217–220.
65. Oslaj, M.; Mursec, B.; Vindis, P. Biogas production from maize hybrids. *Biomass Bioenergy* **2010**, *34*, 1538–1545. [CrossRef]
66. Lin, C.H.; McGraw, M.L.; George, M.F.; Garrett, H.E. Nutritive quality and morphological development under partial shade of some forage species with agroforestry potential. *Agrofor. Syst.* **2001**, *53*, 269–281. [CrossRef]
67. Burner, D.M.; Brauer, D.K. Herbage response to spacing of loblolly pine trees in a minimal management silvopasture in southeastern USA. *Agrofor. Syst.* **2003**, *57*, 69–77. [CrossRef]
68. Alatürk, F. Gübrelemenin Çanakkale ili meralarında verim ve otun kimyasal bileşimine etkileri. Üksek Lisans Tezi, Onsekiz Mart Üniversitesi Fen Bilim, Enstitüsü Basılmamış Çanakkale, Ankara, Turkey, 2012.
69. Gökkuş, A.; Kahriman, F.; Alatürk, F.; Ali, B. Variation of Nutritional Values in Leaves and Stalks of Different Maize Genotypes Having High Protein and High Oil during Vegetation. *Agric. Agric. Sci. Procedia* **2016**, *10*, 18–25. [CrossRef]
70. Wilkie, A.; Goto, M.; Bordeaux, F.M.; Smith, P.H. Enhancement of anaerobic methanogenesis from napiergrass by addition of micronutrients. *Biomass* **1986**, *11*, 135–146. [CrossRef]
71. Weiland, P. Biogas production: Current state and perspectives. *Appl. Microbiol. Biotechnol.* **2010**, *85*, 849–860. [CrossRef] [PubMed]

5 Chapter III

Impact of Different Shading Levels on Growth, Yield and Quality of Potato (*Solanum tuberosum* L.)

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*As shown in the previous Chapter II, shade-intolerant crops like maize, show reductions in plant growth; yield and quality of final biomass and biogas at shading levels greater or equal to 26 %. However, other crops are more tolerant to shade. One of these crops is the C3 plant potato (*Solanum tuberosum *L.). Potato seems better suited for a cultivation under shade conditions and could be a suitable understory crop in AFS. Potato has already been tested in AFS, but most of the AFS were located in the tropics and subtropics. In these regions, high amounts of solar irradiance are available for crop growth, even under shade. At higher latitudes, like in Europe, the solar irradiance is lower than near the equator. An additional reduction in solar irradiance by shade could therefore lead to insufficient plant growth. Chapter III deals with the impact of shade on potatoes. Potatoes were shaded by 0 %, 12 %, 26 % and 50 % using the same experimental setup as in the previous chapter. Yield and growth parameters were determined, also the final tuber mass and quality. The objectives of this study were to evaluate the impact of the mentioned shade levels on potato growth, tuber yield and quality parameters under the given solar irradiance of southwest Germany.*

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Impact of Different Shading Levels on Growth, Yield and Quality of Potato (*Solanum tuberosum* L.)

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Abstract: In agroforestry systems (AFS), trees shade the understory crop to a certain extent. Potato is considered a shade-tolerant crop and was thus tested under the given total solar irradiance and climatic conditions of Southwestern Germany for its potential suitability in an AFS. To gain a better understanding of the effects of shade on growth, yield and quality; a three-year field experiment with different artificial shading levels (12%, 26% and 50%) was established. Significant changes in growth occurred at 50% shading. While plant emergence was not affected by shade, flowering was slightly delayed by about three days. Days until senescence also showed a delay under 50% shade. The number of tubers per plant and tuber mass per plant were reduced by about 53% and 69% under 50% shade. Depending on the year, tuber dry matter yield showed a decrease of 19–44% at 50% shade, while starch content showed no significant differences under shade compared to unshaded treatment. The number of stems per plant, plant height and foliage mass per plant as well as tuber fraction, black spot bruise and macronutrient content were unaffected. Overall, potato seems to tolerate shading and can therefore be integrated in an AFS, and can cope with a reduced total irradiance up to 26%.

Keywords: potato (*Solanum tuberosum*); shade; light; yield; growth; quality

1. Introduction

Due to increasing pressure on cultivated land, intercropping systems may provide an alternative option of economic and environmental interest in temperate regions. Research on temperate intercropping peaked in the 1980s, and was focused on the promotion of sustainable agricultural management strategies [1,2]. These past studies presented intercropping systems as ecologically advantageous when compared to monocultures. Intercropping allows more efficient use of land area, changes the microclimate, improves the biodiversity, offers economic diversity, creates wildlife habitats, and minimizes climate variabilities [3–5]. Within the past decade, research on temperate intercropping has increased because it is considered as an effective strategy to mitigate food insecurities and agriculture-related environmental degradation of land and water. This increased interest is partially associated with recent technological advancements, which improve the labor efficiency potential of the practice [6].

A special form of intercropping is the agroforestry system (AFS). These systems combine an annual agricultural component (crop or livestock production) with a perennial woody component (trees, hedgerows) at the same time on the same area of land [7–9]. The advantages of AFS include increased carbon sequestration, improved water regulation, better soil fertility, reduced erosion, and additional aesthetic value [10–13]. However, in most silvoarable agroforestry systems (a combination of annual crop production with woody perennials), competition not only exists aboveground (competition for light), but also comes from belowground (competition for soil moisture and nutrients), both of which may lead to lower crop yields.

Worldwide, there are numerous options for combining trees and crops in AFS (e.g., alley cropping, forest farming, riparian buffer, silvopasture or windbreaks) [14]. However, most of these systems show a reduction in crop yields due to tree competition, especially when the plantation design is too dense. An example of an AFS is apple trees (*Malus pumila* Mill.) with soybean (*Glycine max* L. Merr.) and peanut (*Arachis hypogaea* L.) in the Loess Plateau region of China. The yields were reduced by about 3–4% in 2.5 m distances to the tree trunk, respectively [15]. An AFS of jujube trees (*Ziziphus jujube* Mill.) and wheat (*Triticum aestivum* L.) in northwest China showed a grain yield reduction of 18% under 4-year-old trees planted with a row distance of 6 m, and a yield reduction of 30% under 6-year-old trees planted with a 3 m row distance compared with the unshaded control [16]. Other experiments with maize (*Zea mays* L.) and beans (*Phaseolus* spp. L.) grown between 15 m wide rows of Paulownia trees (*Paulownia elongate* S. Y. Hu) showed reduced grain yields of 32% and 37%, respectively [17]. Rice (*Oryza sativa* L.) or wheat grown in a 20 m x 20 m field in Western Himalaya together with one row of *Grewia optiva* (J.R. Drumm. ex Burret), *Morus alba* (L.) or *Eucalyptus* spp. hybrids (L'Hér.) in the center of the field, reduced yields of rice by 28–34% and of wheat by 28–29% compared with the control without trees [18]. Beans (*Phaseolus vulgaris* L.) grown under Timor Mountain Gum (*Eucalypthus urophylla* S.T. Blake) in Brazil showed significantly reduced bean yields of almost 50% [19].

Most of these studies examined the reduction of incident radiation as the main factor for reduced yields [15,18,20,21], thus studying the use of shade tolerant crops in an AFS could be advantageous. Such crops are able to reach their light saturation point at lower total solar irradiance, have a better yield performance under shade, and therefore, can be grown in an AFS.

Potato (*Solanum tuberosum* L.) is known to be a shade-tolerant crop. As a C3 plant, potato needs moderate irradiance conditions [22]. Its light saturation point for photosynthetically active radiation (PAR) is considered to be around 400 µmol m^{-2} s^{-1}, which corresponds to 14.86 MJ m^{-2} day^{-1} [23]. Especially in tropical and subtropical zones (0–23.5° N/S and 23.5–40° N/S latitude) where potato can be grown throughout the year and radiation is up to 30 MJ m^{-2} day^{-1}, potato is quite often integrated in an AFS. Studies from Nigeria, Kenya and South Asia show only minor effects on yield by tree shading in AFS.

An experiment in Nigeria showed that growing potato (*Solanum tuberosum* L.) between rows of rattle trees (*Albizia lebbeck* L. Enth.) increased the tuber yield and the number of tubers [24]. Under unfertilized, open field conditions in Kenya, potatoes also obtained higher yields in an AFS with *Eucalyptus grandis* (W. Hill ex Maiden) [25]. An Indonesian experiment that used artificial shading showed that plant height and tuber yield increased under 50% light reduction, compared with full sunlight. The height of some potato cultivars was affected by artificial shade [22]. Such changes in plant height represent a shade avoidance response, with plant height increasing under shade to reach more light. This stimulates the plants and leads to height growth and elongation to obtain more irradiation [26]. In Egypt, taller plants were obtained under colored nets in comparison to the open field [27]. Earlier experiments in Egypt on potatoes found that potatoes grown under low irradiance were taller, but the tubers were smaller and irregularly shaped. Furthermore, the tuber dry weight was reduced under low light conditions [28].

It has been proven that the duration of each potato growth phase determines the later yield [29]. In the tropics and subtropics, there is still enough radiation (even under shady AFS conditions) available to reach the light saturation point of potato. However, it might not be reached at higher latitudes. In the temperate zone of Europe where the growing season lasts from March to October, the amount of radiation available is between 10–20 MJ m^{-2} day^{-1} [30]. Since light has a decisive influence on plant growth, yield is reduced by shade and lower total solar irradiance in higher latitudes, while in lower latitudes competition for water and nutrients has a major effect. So far, little research is available on the impact of shady conditions at higher latitudes on the growth, yield and quality of potato in an AFS under non-tropical conditions. In the few studies on AFS with potatoes in temperate (potatoes and hazel (*Corylus avellane* (L.)) and subarctic zones (potatoes and willow (*Salix* sp. (L.)), experiments have mainly focused on potato cultivation beside windbreaks [31–33]. Beside these windbreaks, other abiotic factors such as wind reduction, reduced soil evaporation, reduction of mechanical stimulus (e.g., twisting of plants) have an influence on growth and yield, and water and nutrients are also affected. In an AFS, these interactions make it difficult to determine the influence of shade. Therefore, the influence of shade has to be determined by artificial shading.

The objectives of this study were to evaluate the impact of four different shade levels (0%, 12%, 26% and 50%) on potato growth, tuber yield and quality parameters under the given total solar irradiance of Southwestern Germany. The determined threshold could be an indicator for farmers as to which level of shade potato cultivation might be profitable. Fertilization or irrigation can compensate for some limitations, but a reduction in light cannot be mitigated.

2. Materials and Methods

2.1. Site Conditions and Experimental Design

The field experiment was carried out from 2015 to 2017 in Southwest Germany at the Centre for Agricultural Technology Augustenberg (LTZ) in Rheinstetten-Forchheim (48°58′ N, 8°18′ E, 117 m above sea level). The site is located in the lower Rhine valley on a Luvisol (60.2% sand, 13.7% clay and 26.1% silt) soil. The mean long-term annual precipitation was 742 mm and the average temperature was 10.1 °C (1981–1990). During the main growing season at this site (April to October), the mean average total solar irradiance from 2009 to 2017 amounted to 17 MJ m^{-2} day^{-1}. Weather data were collected in a linear distance of 270 m from the experimental site. Total solar irradiance was measured by a SCAPP (scanning pyrheliometer and pyranometer, Fa. Siggelkow Gerätebau, Hamburg). The monthly air temperature averages, cumulative precipitation and average total solar irradiance for the experimental years are given in Figure 1. In all of the experimental years, the previous crop was winter barley. Different green manure crops were incorporated in the potato experimental plots during the winter months of each experimental year. Green manure crops included 25 kg ha^{-1} *Sinapsis alba* L. in 2014/2015, 18 kg ha^{-1} flower mixture (FAKT M2, BSV Saaten; 20.0% leguminosae, 6.0% rough leguminosae, 27.5% herbs, 46.5% others [34]) in 2015/2016 and 25 kg ha^{-1} *Raphanus sativus* L. cv. 'Denfender' in 2016/2017.

On 20 September 2014 (day of the year (DOY) 263), primary tillage was done with a moldboard plough (25 cm depth). Potatoes were planted on 16 April 2015 (DOY 106), 13 April 2016 (DOY 104) and 13 April 2017 (DOY 103) after secondary tillage with a chisel plow (15 cm depth). The mid-early potato variety 'Selma' (*Solanum tuberosum* L., Bavaria Saat) was planted with a row distance of 0.75 m and an intra-row distance of 0.35 m, which resulted in four plants per m^2. The experimental design was a randomized complete block design with three replicates. Plots were 10 m long and 6 m wide, consisting of a total of 8 rows per plot. Core plots for tuber harvest were 8 m long and 1.5 m wide, including two rows and leaving three rows on the left and right as a border. Planting depth was 5 cm. Hoeing and earthing up was done prior to pre-emergence herbicide application. Amount of fertilizer was calculated based on nutrient removal. The date, amount and type of fertilizer is shown in Table 1. Fertilization was done by a pneumatic centrifugal spreader (RAUCH AERO 2212, Sinzheim, Germany). Plant protection was done based on the risk assessment of the online tool 'ISIP' [35]. The amount and type of pesticides are given in Table A1 in the Appendix A. Plant protection was conducted according to the codes of "Good Agricultural Practice in Plant Protection and Fertilization" [36]. Irrigation was done by an overhead irrigation-gun on 29 May 2015 (DOY 149), 29 June 2015 (DOY 180), 7 July 2015 (DOY 188), 16 July 2015 (DOY 197), 3 August 2015 (DOY 215), 7 July 2016 (DOY 189), 13 July 2016 (DOY 195), 29 July 2016 (DOY 211), 12 August 2016 (DOY 225), 31 August 2016 (DOY 244), 31 May 2017 (DOY 151), 20 June 2017 (DOY 171) and 4 July 2017 (DOY 185), with 30 mm of water at each irrigation event. The irrigation was based on the recommendations of the online irrigation tool, 'Agrowetter' [37]. Harvest was conducted using a one-row potato elevator-digger (Niewöhner Wühlmaus, Weimar, Germany) on 8 September 2015 (DOY 251), 6 September 2016 (DOY 250) and 6 September 2017 (DOY 249).

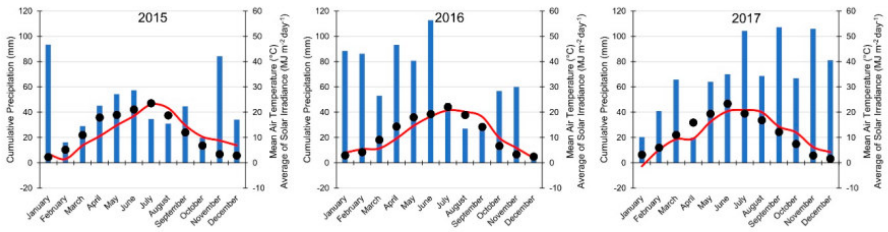

Figure 1. The monthly cumulative precipitation (mm, blue bars), mean air temperature (°C, solid, red line) and average total solar irradiance (MJ m^{-2} day^{-1}, filled, black circles) during the experimental years 2015 to 2017 at Rheinstetten-Forchheim.

Table 1. Date, amount, active ingredient and pure nutrient amount of the applied fertilizer. The day of the year (DOY) is given in parentheses beneath the corresponding date.

Date	Fertilizer	Active Ingredient	Pure Nutrient
16 April 2015 (DOY 106)	130 kg ha^{-1} lime-nitrogen	20% N, 50% CaO	26 kg N, 46 kg Ca
	300 kg ha^{-1} ALZON46	46% N	138 kg N
	600 kg ha^{-1} potassium sulfate with magnesium	23% P_2O_5, 9% S	60 kg P, 54 kg S
	200 kg ha^{-1} superphosphate 18	18% P_2O_5, 12% S	16 kg P, 24 kg S
11 April 2016 (DOY 102)	350 kg ha^{-1} lime-nitrogen	20% N, 50% CaO	70 kg N, 125 kg Ca
12 April 2016 (DOY 103)	260 kg ha^{-1} calcium ammonium nitrate	27% N	70 kg N
	450 kg ha^{-1} superphosphate 18	18% P_2O_5, 12% S	35 kg P, 54 kg S
	1110 kg ha^{-1} sulphate of potash containing magnesium salt	30% K_2O, 10% MgO, 17% S	276 kg K, 67 kg Mg, 189 kg S
13 April 2017 (DOY 103)	260 kg ha^{-1} ALZON46	46% N	120 kg N
	970 kg ha^{-1} sulphate of potash containing magnesium salt	30% K_2O, 10% MgO, 17% S	242 kg K, 58 kg Mg, 165 kg S
27 April 2017 (DOY 117)	390 kg ha^{-1} superphosphate 18	18% P_2O_5, 12% S	31 kg P 47 kg S

2.2. Shading Levels

Shading was created by nets which reduced the incoming solar radiation by 12%, 26% and 50%. The different shading levels were compared with full sunlight (0% shade). The nets were made of polyethylene and had different mesh sizes to create the different shading levels. The 12% net had a mesh size of 3 × 8 mm and was black; the 26% net had a mesh size of 12 × 12 mm and was green, and the 50% net had a mesh size of 3 × 3 mm and was green (AGROFLOR Kunststoff GmbH, Wolfurt, Austria). Nets were installed at the time of potato emergence (growth stage (GS) 009 according to [38]), on 20 May 2015 (DOY 140), 10 May 2016 (DOY 131) and 9 May 2017 (DOY 129). Nets were clipped on to steel wires, which were connected between wooden posts. The height of the nets could be adapted to the plant growth, and to 1 or 2 m in height. A distance of 0.5 m between the nets and canopy surface was guaranteed. Further information about the experiment layout can be found in Schulz et al. [39]. Table 2 shows the total incoming daily solar irradiance at the experimental site from the time of the potato crop emergence (Growth Stage (GS) 009) to the tuber harvest (GS 909) for each experimental year and the theoretically reduced incoming total solar irradiance under the shading nets.

Table 2. The calculated total solar irradiance for the shading treatments during the period without shading (-S, planting growth stage (GS) 000 to emergence GS 009), the period with shading (+S, emergence GS 009 to harvest GS 909) and the whole growing period (GP, planting GS 000 to harvest GS 909) (MJ m^{-2} day^{-1}), the duration of these time periods (days) is given in parentheses.

		Total Solar Irradiance (MJ m^{-2} day^{-1})								
	Year	**2015**			**2016**			**2017**		
	Time Period	**-S (26)**	**+S (112)**	**GP (138)**	**-S (26)**	**+S (121)**	**GP (147)**	**-S (32)**	**+S (115)**	**GP (147)**
Shading level	**0%**	18.52	20.22	19.90	17.70	19.15	18.90	14.87	20.13	18.96
	12% ‡		17.80	17.93		16.86	17.00		17.72	17.08
	26% ‡		14.97	15.64		14.17	14.80		14.90	14.89
	50% ‡		10.11	11.70		9.58	10.01		10.07	11.14

‡ values for +S were calculated by subtracting the light reduction by nets from the measured total irradiance at 0% shade.

2.3. Data Collection and Analysis

2.3.1. Growth Parameters

In 2015, no growth parameters were determined; only the tuber dry matter yield and quality were determined. During the vegetation periods 2016 and 2017, destructive and non-destructive measurements were done. Growth stages according to the BBCH-scale were determined twice a week [40]. Potato plant height measurements were obtained every week during the emergence stage (GS 009) through to tuber formation (GS 405) on four plants per plot. Plant height was determined using a meter stick to measure the highest point of the soil surface to the highest point of the plant canopy. When the potato plant flowers, the stem and leaves have reached their maximum growth (GS 405), and tubers have reached 50% of their final mass (GS 625) [33–35]. Due to the high workload at GS 405/625, two plants per plot were randomly selected from the 3rd or 6th row and harvested for further observations. The observed parameters were stems per plant, tubers per plant, tuber mass per plant, total foliage mass per plant (including all above ground biomass; leaves, stem, flowers, berries), the ratio between foliage and tuber mass, total mass per plant and the harvest index (HI). Leaf area (LA) was determined using Equation (1):

$$LA = LL \cdot LW \cdot 0.55, \quad (1)$$

where LL is the leaf length from leaf tip to leaf attachment at stem, LW is the maximum leaf width and 0.55 is a constant [41]. Leaf length and the width of a leaf from the middle leaf layer were measured with a meter-stick. The leaf was dried for three days at 60 °C and the specific leaf area (SLA) was calculated. LA and SLA were only determined in 2017. Growing degree days (GDD) were calculated using Equation (2), where i is the day between planting (P) and harvest (H):

$$GDD = \sum_{i=P}^{H}\left(\frac{T_{max_i} + T_{min_i}}{2} - T_{base}\right). \quad (2)$$

For potato, a base temperature (T_{base}) of 6 °C was assumed since no sprout growth is expected at lower temperatures [42–45]. If T_{max} or T_{min} at day i were smaller than T_{base} they were set to T_{base} [46].

2.3.2. Yield Parameters

In all years, all harvested tubers from the center rows of each plot were weighed to calculate yield on a hectare basis. Then, a sub-sample of 2 kg per plot were fresh weighed, oven-dried (1 week, 105 °C) and the dry weight was determined to calculate the dry mass and substance. In 2016 and 2017, all fresh-harvested tubers per plot were sorted according to the size classes: <30 mm (undersized fraction), 30–60 mm (table fraction), and >60 mm (oversized fraction) [47]. Selma is listed in the German variety list as a variety that has long oval tubers [48].

2.3.3. Quality Parameters

An additional sub-sample of 2 kg from the harvested tubers per plot was used to determine nitrogen (N) via the combustion method after Dumas, and phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) via spectrometry [49–51]. Analysis of starch content was done according to the polarimetry method [52]. Sub-sample of 30 tubers per plot between 30–60 mm were analyzed for black spot bruise [47]. The black spot bruise index (BSB) was calculated from the number of light, middle and strong discolored tubers ($tuber_{light}$, $tuber_{middle}$, and $tuber_{strong}$, respectively):

$$BSB = \frac{\left(0.3 \cdot tuber_{light}\right) + \left(0.5 \cdot tuber_{middle}\right) + tuber_{strong}}{tuber_{total}} \times 100. \quad (3)$$

A tuber is counted as light discolored when 1/4 of the circumference is discolored to a 5 mm depth. A tuber is counted as middle discolored when 1/4 of the circumference is discolored and this discoloration is deeper than 5 mm and/or when half of the circumference is discolored to 5 mm. A strong discoloration occurs when tubers are discolored up to half of the circumference and are discolored deeper than 5 mm and/or more than 1/2 is discolored up to 5 mm depth. To measure BSB, samples were spun in a washing machine for 45–90 s (determination of the time took place every year with a standard potato variety). Afterwards, samples were stored for 4–5 days at room temperature. Then the tubers were cut at the greatest diameter and the number of tubers with discoloration (blue, grey or black) was determined [53].

2.3.4. Data Analysis and Statistics

Analysis of the yield data was performed for each year by using the following fitted model:

$$\boldsymbol{y_{ij}} = \mu + \boldsymbol{r_i} + \boldsymbol{s_j} + \boldsymbol{e_{ij}}, \quad (4)$$

where y_{ij} is the tuber dry matter yield, μ the general effect, r_i is the fixed effect of the i-th replicate, s_j is the fixed effect of the j-th shading level and e_{ij} is the residual error of $y_{ijk.}$

For the analysis of repeated measurements (duration of growing phases, number of stems per plant, number of tubers per plant, tuber mass per plant, foliage mass per plant, foliage:tuber mass ratio, total mass per plant and HI) on two plants per plot at GS 405/625 the model was as follows:

$$\boldsymbol{y_{ijk}} = \mu + \boldsymbol{r_i} + \boldsymbol{s_j} + (\boldsymbol{rs})_{ij} + \boldsymbol{e_{ijk}}, \quad (5)$$

where y_{ikj} is the response, μ the general effect, r_i is the fixed effect of the i-th replicate, s_j is the fixed effect of the j-th shading level, $(rs)_{ij}$ is the random plot effect where the j-th shading level is used in the i-th replicate, and e_{ijk} is the residual error of y_{ijk} which corresponds to the k^{th} plant effect in the ij^{th} plot. For both models the PROC MIXED procedure of Statistical Analysis Software SAS, version 9.4 (SAS Institute Inc., Cary, NC, USA) was used.

The multi-year analysis of quality data (macronutrients: nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) was done by using the Residual Maximum Likelihood of the PROC MIXED procedure of SAS. The following linear mixed model was fitted:

$$y_{ijl} = \mu + a_l + s_j + (ra)_{il} + (as)_{lj} + e_{ijl}, \tag{6}$$

where y_{ijl} is the response, μ the general effect, a_l is the fixed effect of the l-th year, s_j is the fixed effect of the j-th shading level, $(ra)_{il}$ is the fixed effect of the i-th replicate in the l-th year, $(as)_{lj}$ is the random interaction effect between the l-th year and the j-th shading level, and e_{ijl} is the residual error of y_{ijl}. For all models, the assumptions of normality and homogenous variances of residuals were checked graphically. If necessary, that is, if the AIC decreases, year-specific error variances were fitted. In all cases, after finding significant differences via the F-test, differences between treatments were compared at α = 5% using Fisher's least significant difference test (LSD). More information on the statistics used can be found in Schulz et al. [39].

The growth parameters for plant height were fitted for each plot with the function 'nls' of the R packages 'nlstools' and 'car' [54,55]. The non-linear regression matched the following equation:

$$y = \frac{\theta_1}{1 + e^{-(\theta_2 + \theta_3 \cdot GDD)}}, \tag{7}$$

where y is the dependent variable for height in the single years 2016 and 2017, θ_1 is the asymptote of the dependent variable, θ_2 is the parallel shift, θ_3 the slope of the function; and GDD are the growing degree days, calculated after Equation (2). Estimates for θ_1, θ_2 and θ_3 from each plot were then submitted to multi-year analysis via model (6).

3. Results and Discussion

3.1. Growth and Development

In 2016 and 2107, artificial shading started after emergence (GS 009), therefore, shading had no influence on the emergence of the potatoes (Table 3). These results agree with an experiment with diverse potato cultivars in the Philippines, where uniform plant emergence was observed at 54% shading and at full light [56]. Because potatoes do not have photosynthetically active biomass until emergence, a change in total solar irradiance has no direct effect on the emergence of plants by influencing their radiation use. However, an indirect influence due to changing soil temperature and moisture might occur. Our study revealed that flowering initiation (GS 601) was prolonged at shading levels >12% shade. In 2017, there was only a significant prolongation under 50%, from 440 GDD under 0% to 467 GDD under 50%. The time from flowering initiation to senescence initiation (GS 901) was prolonged from 973 GDD under 0% and 12% shade to 1211 GDD under 26% and 50% shade. In 2017, no change was observable between 12% and 26% shade compared with 0%. This can be explained by differing climatic conditions in 2016 and 2017. In 2016, the 26% and 50% shade treatment needed a higher amount of GDD to reach senescence due to the cooler and rainy growing period. The light saturation of 14.86 MJ m^{-2} day^{-1} could not be reached. The rainy period lasted from April to June (Figure 1). During these months the total solar irradiance was lower (14.34, 18.02 and 19.28 MJ m^{-2} day^{-1}) than in 2015 (17.94, 18.93 and 21.08 MJ m^{-2} day^{-1}) and 2017 (15.9, 19.38 and 23.39 MJ m^{-2} day^{-1}). Table 2 showed that in 2016 the light saturation point of potatoes could not be reached at levels of 26% and 50% shade, while in 2015 and 2017 this was only observable under 50% shade. The time from senescence initiation until harvest day (GS 909) in both 2016 and 2017, did not show any significant changes by shade. The harvestable tuber yield was determined by the duration of the growing season. This was also shown in a Dutch experiment. The authors observed that the growth of potato plants and the dry matter production of tubers were mainly determined by the duration of its growth cycle [29], that is, the duration of each single growth phase is important for the later yield.

The authors of the study concluded that the development depends on temperature and daylength. At higher latitudes (e.g., >55° N) growth limitations could occur due to cooler temperatures, which do not fit the optimum values for the single growing phases.

Table 3. Duration of growing phases in Growing Degree Days (°Cd) and the range of days from planting to emergence (P-E), emergence to flowering initiation (E-F), flowering initiation to senescence initiation (F-S) and senescence initiation to harvest day (S-H) in 2016 and 2017 for the four shading levels (0%, 12%, 26% and 50%). From planting to emergence is a phase without shading (-S), from emergence to harvesting potatoes were shaded (+S; see also Table 2). Phases correspond to the GS 000 to 009 (P-E), 009 to 601 (E-F), 601 to 901 (F-S) and 901 to 909 (S-H). SEM gives the standard error of means.

		Duration of Growing Phases							
		-S		+S					
Year	**Shade**	**P-E**		**E-F**		**F-S**		**S-H**	
		GDD	**days**	**GDD**	**day**	**GDD**	**days**	**GDD**	**days**
2016	**0%**	132	26	559 c †	42	973 b	30	1689	48
	12%	132	26	573 b	43	973 b	29	1685	48
	26%	132	26	580 b	44	1211 a	43	1685	33
	50%	137	26	598 a	45	1211 a	42	1685	33
	SEM	2.24		3.62		0.00 ‡		2.03	
		p-values $							
	Replicate	0.422		0.422		1.000		0.422	
	Shade	0.455		0.002		<0.0001		0.455	
2017	**0%**	169	32	440 b	21	1003	39	1755	54
	12%	173	32	447 b	21	1016	39	1768	54
	26%	173	32	444 b	21	1011	39	1764	54
	50%	169	32	467 a	24	1007	36	1760	54
	SEM	2.93		2.79		4.17		4.02	
		p-values $							
	Replicate	0.670		1.000		0.823		0.708	
	Shade	0.654		0.002		0.249		0.243	

† Means with identical letters within each column and year show non-significant differences between the shade levels of the single years (LSD test, $\alpha \leq 0.05$). ‡ Note: The SEM was between 0 and 0.005, so rounding to two decimal places resulted in a SEM of zero. $ *p*-value for the *F*-test of the corresponding factor.

An experiment conducted in the Philippines showed no significant change in plant height at different light intensities for potatoes grown in December (long-day), while potatoes grown in March (short-day) showed differences [56]. Under short-day conditions potatoes develop a canopy, which causes faster senescence and low tuber yields. Since the plants do not receive enough irradiation, they get into a stress situation and start to relocate their nutrients from the leaves to the generative organs, which causes senescence of the leaves. Under long-day conditions the above-ground organs do not die off as quickly and can use the solar irradiance longer and generate higher yields. An additional shade under short-day conditions can delay development and so, the potato growth phase is prolonged. Additionally, high temperatures reduce the above-ground biomass. Potatoes grown under temperatures of 17 °C showed dry matter production of 22.8 g m^{-2} day^{-1} [57], while under higher temperature, biomass is reduced. To detect if artificial shade affects plant height at higher latitudes, plant height obtained from our experiment was fitted using a sigmoid growth curve. Results indicated that the year-specific and/or shading level-specific curve determining parameters, θ_1, θ_2 and θ_3 for the trait plant height (Equation (7)) were not significantly different from each other (the test for year-specific parameters showed p = 0.607, p = 0.076 and p = 0.826 for θ_1, θ_2 and θ_3, respectively; the test for shade-specific parameters showed p = 0.649, p = 0.282 and p = 0.837 for θ_1, θ_2 and θ_3, respectively). Thus, a single curve across both years can be fitted. This indicates that there were no significant effects of shading and year on plant height. The observed values and the fitted curve are shown in Figure 2. Note that year-by-shade interactions were assumed as random in Equation (6).

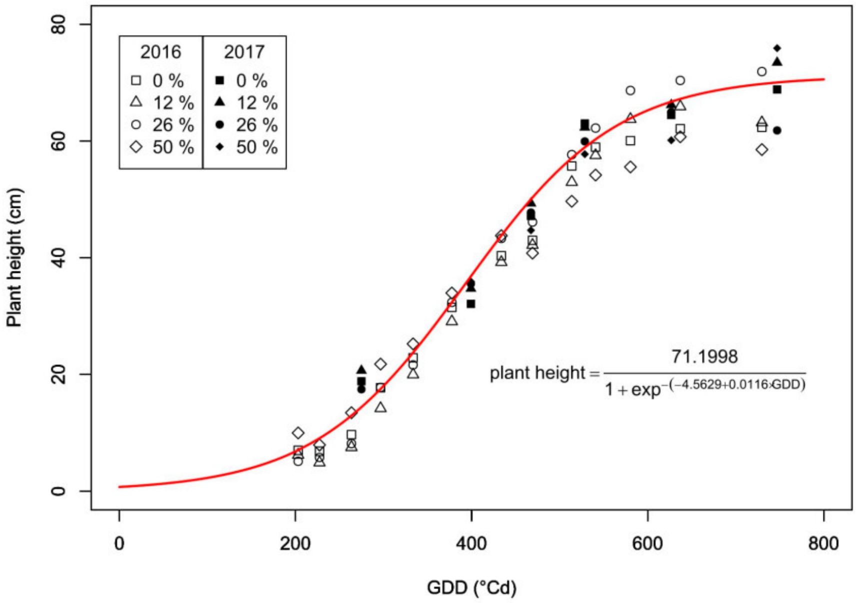

Figure 2. Average values for the observed (symbols) plant height (cm) depending on GDD (°Cd) for the four shade levels and the two years; 2016 (0% open square, 12% open triangle, 26% open circle and 50% open diamond) and 2017 (0% filled square, 12% filled triangle, 26% filled circle and 50% filled diamond) and the fitted growth function (solid, red line) for plant height over all shade levels and years.

In 2016, the control and 26% shade plants reached their maximum height after 730 GDD (62.3 and 72.2 cm). Plants in the 12% and 50% shading treatments reached their maximum heights after 637 GDD with 65.9 and 60.7 cm, respectively. In the second year, all treatments, with the exception of the 26% treatment, reached their maximum height after 747 GDD (68.8, 73.5 and 75.9 cm). Plants in the 26% shading treatment reached their maximum after 627 GDD at 65.0 cm. In Sri Lanka, potatoes in an AFS with Leucaena leucocephala ((LAM.) DE WIT) showed no changes in plant height [58]. No change in plant height was observed when potatoes were intercropped with maize in a tropical experiment in Uganda [59]. An experiment in temperature-controlled cabinets showed an increase in plant height only at radiations below 7.7 MJ m^{-2} day^{-1} [60]. The authors related the increase in plant height to increased gibberellin activity under shade and a reduced assimilation of CO_2. Table 2 shows that in the current study, the total solar irradiance never fell below 7.7 MJ m^{-2} day^{-1}, resulting in no difference in plant height as shown in Figure 2. In addition, the cultivar was a strong influence on the growth of the potato [61]. At lower latitudes, two out of four shaded potato cultivars showed no changes in height. One cultivar showed an increase in height at 30% shade, and the other cultivar at 50% shade [22]. The authors ascribed this to a higher auxin level while the gibberellin level also increased, which promoted stem growth. These results suggest that the cultivar plays a crucial role in height growth under shade. Abu-Zinada and Mousa generally attributed height changes to genetic differences in different potato cultivars [62]. A study of a shade-effect on different phytohormones showed that due to the total irradiance reduction and the associated change in the wavelength spectrum, changes in phytochrome B occurred, which led to growth expansion [63].

3.2. Yield Determining Parameters and Yield

The tuber yield of potatoes is influenced by various factors such as nitrogen, cultivar, planting density and spacing of planting tubers, climatic conditions and geographic location [64]. The four main tuber yield determining growth parameters are the number of plants per hectare, number of stems per plant, number of tubers per plant and average tuber weight per plant [65]. The experiment revealed no changes in the number of plants per hectare under the different shade levels. This is due to the fact that the shade was only established after potato emergence. As discussed above, a change in solar total irradiance does not affect plant emergence directly; so, all planted potatoes were able to emerge (Table 2).

Table 4. Mean growth parameters for two potato plants under four different shade levels (0%, 12%, 26% and 50%) evaluated in 2016 and 2017 at GS 405/625 (maximum foliage growth was reached); number of stems per plant, number of tuber per plant, tuber mass per plant (g), foliage mass per plant (g), foliage:tuber mass ratio (%), total mass per plant (g) and the harvest index (HI). SEM gives the standard error of means.

Shade	Number of Stems per Plant	Number of Tubers per Plant	Tuber Mass per Plant	Foliage Mass per Plant	Foliage:Tuber Mass Ratio	Total Mass per Plant	HI
Year			**2016**				
0%	2.50	10.50	44.47	48.21	1.32	92.68	0.45
12%	3.67	12.44 ⊥	56.70	57.06	1.25	113.76	0.48
26%	4.17	12.83	49.81	75.45	2.45	125.25	0.36
50%	4.17	13.67	36.28	57.05	1.81	93.33	0.39
SEM	0.85	2.79	10.97	9.98	0.53	19.66	0.04
			***p*-values $**				
Replicate	0.248	0.144	0.104	0.509	0.092	0.488	0.002
Shade	0.479	0.873	0.612	0.300	0.417	0.585	0.213
Year			**2017**				
0%	4.83	19.00 a †	103.60 a	79.37	0.95 b	182.97 a	0.54
12%	3.50	17.83 a	51.28 b	64.70	1.58 b	115.98 b	0.43
26%	3.17	13.17 ab	66.32 ab	62.15	1.00 b	128.47 ab	0.52
50%	3.33	9.00 b	32.68 b ‖	60.07	4.67 a ∇	86.12 b	0.25
SEM	0.51	2.47	14.05	10.59	0.92	21.15	0.06
			***p*-values $**				
Replicate	0.835	0.605	0.510	0.259	0.573	0.473	0.788
Shade	0.186	0.038	0.020	0.575	0.051	0.032	0.064

† Means with identical letters within each column and year show non-significant differences between the shade levels of the single years (LSD test, $\alpha \leq 0.05$). ⊥ SEM for 12% shade ± 3.08 due to missing value. ‖ SEM for 50% shade ± 15.53 due to missing value. ∇ SEM for 50% shade ± 1.02 due to missing value. $ *p*-value for the *F*-test of the corresponding factor.

The different shading treatments had no significant impact on the number of stems per plant in either year (2016 $p = 0.479$ and 2017 $p = 0.186$) (Table 4). Studies showed that the number of stems depended on the size of the seed tubers or potato variety, but not on the given environmental factors [59]. Genotype is also an influence on the number of produced stems [66]. Other sources also show that the age of the planted tubers influences the number of stems. Young tubers produced one stem and older tubers more stems [67]. A study conducted in the Philippines showed that the number of stems per plant was not affected by a shade level of 54% [56]. Another study showed that number of stems was determined by the number of sprouts, which is influenced by moisture, temperature and structure of soil, and the number of plants per hectare [66]. Since the development of sprouts into stems takes place below-ground, the shade only impacts soil temperature and moisture. In our experiment, shade nets were installed after emergence. By this time sprouts were already developed. In a real AFS where the distance between single trees is wide enough, and trees are pruned and/or varieties with thinner crowns are used, their influence on soil temperature and moisture will be quite small, therefore, this potential influence on sprouts and emergence can be neglected.

Every stem produces leaves, which are photosynthetically active. As described above no change in the number of stems per plant was determined, therefore no effect on the foliage mass per plant was observable. Even in a rather overcast year like 2016, plants did not compensate for the reduced total solar irradiance with increased photosynthetically active biomass. However, shading is often accompanied by a changed in the partitioning of dry matter between the source and sink organs. In 2017, the number of tubers per plant were significantly reduced at a shade level of 50%. An experiment in the United Kingdom with different potato cultivars showed that the cultivar 'Estima' showed no change in time of tuber initiation up until to an artificial shading of 75%, while 'Maris Piper' showed delayed tuber initiation in shading of 50% or more [68]. Since the cultivar remained the same every year, it is suspected that the reduction in 2017 was caused by environmental factors (e.g., soil temperature or moisture) other than irradiance reduction. On average, the number of tubers was reduced by ten tubers per plant compared with the control. The studies of Sun and de Luca et al. showed a decrease in the number of tubers per plant under 54% shade and attributed this to a shade induced increase in the gibberellin (GA) content [69,70]. Studies with peas (*Pisum sativum* L.), lotus (*Nelumbo* spp. Adans.) and *Brassica* spp. (L.) at different shade levels also showed a higher GA, therefore, the change of GA under shade seems to be important for plant development, especially for tuber formation [71,72]. In potatoes, higher content of GA has been shown to inhibit tuber formation [20,47,50,58]. Wurr et al. found a reduced number of tubers under field conditions at a shade level of 70% in experimental sites in the United Kingdom [73]. The authors attributed this to a reduced number of stolons, which was caused by lower temperatures slowing down growth. The number of stolons formed indicate the final tuber number. The number of tubers per plant is initiated in a very short time of ten days, the maximum number is reached when shoot dry matter starts to decrease [74]. Ewing et al. observed that tuber formation is promoted by soil moisture [75]. It is possible that in 2016, the naturally occurring low total solar irradiance in combination with the shading provided more moisture than in 2017, leading to a significant reduction in the number of tubers formed in 2017. The results show that less tubers with lower weight were observed in 2017 under 50% shade compared with 0%. Pohjakalli stated that tuber weight decreased about 80% at light intensities of 67% to 33% of full sunlight (which corresponds to 33% to 67% shade) [76]. A Philippine experiment showed that depending on the cultivar, under 54% shade a reduction in dry matter weight of tubers can be determined between 0% and 80 % compared with potatoes grown under full sunlight [77]. Under 74% light (corresponds to 26% shade) most of the used cultivars showed a reduction of up to 29%. Under 30% shade, 3% more tubers were formed, while under 50% shade there was an increase of about 55% [78]. In tomatoes, it has been observed that during the bulking period, the radiation use efficiency is highly related to fruit development because at this time the canopy is fully developed [79]. In our experiment, we observed that the onset of bulking occurred even under shaded conditions. During this time, in 2016 only the 0% and 12% shade, and in 2017 all treatments except for the 50% received adequate total solar irradiance for light saturation.

Our results showed no significant changes in the foliage mass per plant under the different shade levels in any experimental year. Mean values ranged from 48.21 g (0%) to 75.45 g (26%) in 2016 and 60.07 g (50%) to 79.37 g (0%) in 2017 (Table 4). This corresponds well with the results for plant height (Figure 2). The literature shows that the rate of foliage development is highly dependent on the cultivar. Some cultivars grow faster than others. Also, the age of the seed tubers affects the foliage, while older tubers enhance the foliage production [56]. Data on leaf area (LA) and specific leaf area (SLA) were only available for 2017. However, no significant differences between the shade treatments (LA p = 0.772

and SLA $p = 0.963$) were observed. Another experiment with 50% and 90% shaded potato leaves showed that shading up to 50% also did not influence LA. However, shading levels of 90% showed a decline in green leaf area. The authors postulated that shading reduces the transpiration, and so, the distribution of cytokinins. Parts which are exposed to more light or less shade have a higher amount of cytokinins, which can promote cell division, branching and leaf growth at shading levels >50% [57].

Foliage mass showed no change based on the tested shading treatment; however, in combination with a decreased tuber mass in 2017, a shift to the above-ground biomass occurred. The ratio changed from 0.95 in the control to 4.67 at the 50% shade level. This shift has been documented in the literature [42]. Under low irradiance (2000 to 3000 lux or lower) a shift to the aboveground biomass occurred, which was not observed under high irradiance (8000 to 16,000 lux). An increase in above-ground biomass growth and an increase in below-ground biomass was also observed in maize plants under 69% artificial shade [80]. In 2016, the potato plants received more total solar irradiance during the phase without shading (until emergence) than in 2017 (17.70 and 14.87 MJ m^{-2} day^{-1}, Table 2). Until onset of tuber initiation, most dry mass was partitioned in leaves and stems and after this time in tubers. If light is reduced, the plant will use more assimilates for leaf mass than for tubers to provide an adequate level of photosynthesis. This can be seen in Table 4. Leaf mass showed no change under reduced light as the plant tried to provide an adequate amount of photosynthetically active biomass, while the tuber mass was reduced.

The lower number of tubers in 2017 and the constant starch content is in line with results found in the literature. Under shade, more sugar is needed to provide photosynthetically active leaf mass. The large amount of sugar that is translocated in the tubers to form starch (because tubers are not photosynthetically active) cannot be covered [81].

As mentioned above, potatoes grown under optimum conditions are able to form 22.8 g of biomass per m^2 and day. Total mass per plant only showed significant changes in 2017. Biomass in the 50% shading treatment was reduced by almost 100 g compared to the control. In 2017, the 0% shade had a radiation use efficiency (RUE) of 2.41 g MJ^{-1} which fits well with the values mentioned in the literature [82]. The 50% shade had a RUE of 1.14 g MJ^{-1}.

The harvest index (HI) could not be determined for the core plot due to defoliation for facilitated harvest. Therefore, the HI was determined at GS 405/625. Table 4 shows that there was no influence from shade prior to defoliation, neither in 2016 nor in 2017. Therefore, the trend of a decreasing HI with increasing shade was observed.

Dry matter tuber yield (DMY, Figure 3) was significantly reduced by shade in 2016 ($p = 0.040$) and 2017 ($p = 0.004$), but not in 2015 ($p = 0.467$). Under 26% shade DMY was significantly reduced by 44% in 2016, while in 2017 a significant reduction of 44% occurred at 50% shade. This is related to the total solar irradiance values in Table 2. The light saturation point of potatoes was reached in 2015 and 2017 in up to 26% shade. Since the plants were able to cover their need for total solar irradiance of 14.86 MJ m^{-2} day^{-1} during the shaded time, no significant changes were observable (Table 2). Both 2015 and 2017 were rather sunny years, while in contrast, spring 2016 had comparatively low total solar irradiance. In June 2016, hot and dry phases alternated with rainfall events. Light saturation was reached up until 12% shade (Table 2). These observations in combination with the already discussed changes, suggest that the phase after emergence is crucial for yield formation, especially since the plant has no photosynthetically active biomass before emergence that can use the light. Figure 3 and Table 2 suggest that the light saturation point does not necessarily have to be met to generate adequate yields. In 2015, even a total solar irradiance of 10.11 MJ m^{-2} day^{-1} from emergence to harvest showed no yield changes. In 2017, the 50% shading received 10.07 MJ m^{-2} day^{-1} after emergence. This indicates that after emergence, potatoes need a total solar irradiance >10.11 MJ. In 2016, the weather was very unsteady, and yield was probably more influenced by temperature, which led to a cooling of the dam (soil piled up to 30 cm). Under air temperatures near optimum, more tubers than shoots are built. When air temperature increases, there is a shift to more shoot biomass than tuber mass [83]. If the air temperature is below the base temperature there will be no growth, neither above-ground nor below-ground.

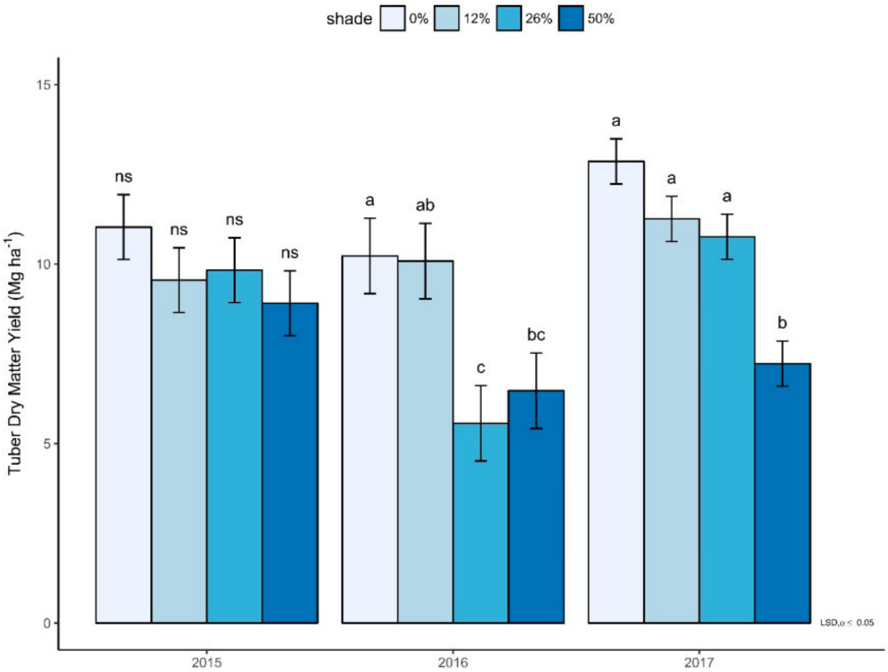

Figure 3. Tuber Dry Matter Yield (Mg ha^{-1}) for the different shade levels (0%, 12%, 26% and 50%) in the single experiment years. Black bars represent the standard error of mean. Means with identical letters within one year show non-significant differences between the shade levels (LSD, $\alpha \leq 0.05$).

Demagante and Vander Zaag indicated that shading of 54% led to total dry matter yields similar to those under full sunlight in the Philippines [56]. A series of experiments in The Netherlands, Rwanda and Tunisia revealed that the tuber dry matter production is highly dependent on growth duration, which is determined by temperature and daylength [29]. The Netherlands is located in a zone with temperate climate and long-day conditions which fits best to the long-day requirement of potatoes, Rwanda is located under short-day conditions with high temperatures, and Tunisia is located in an interface zone between long- and short-day conditions with adequate temperatures from October to April. Hence, as potato is a long-day plant requiring a maximum temperature of >20 °C, Rwanda with its short daylength and high temperature could be unfavorable, while in The Netherlands and Tunis the day-length during the growing period is adequate. However, shading can lower the temperature unfavorably and a short day-length hastens tuber initiation, which reduces the final tuber yield [84]. Kuruppuarachchi showed that shading potatoes at a level of 50% by suspended coconut leaves during the whole cropping season reduced tuber yield significantly by about 56% in Sri Lanka [58]. He concluded that permanent shading compared with shade in the first four weeks resulted in variation in the day/night temperatures of the soil, which may be unfavorable for tuber growth. A study by Sale with potatoes shaded at a level of 34% throughout the growing period showed a 26–42% decrease in yield [85]. Cultivation of potato beneath stone pines (*Pinus pinea* L.) reached tuber yields of 60-86% yield when compared with the national average yields [86].

Experiments with 30% and 50% shade have showed reduced yields by approximately 2–56% [78]. In 2016 and 2017, we also observed a 50% reduction in yield under 50% shade.

Overall, the yield reductions in our experiment are comparable with the results of other experiments, mostly from tropical countries where irradiance is in general much higher. Therefore, it can be concluded that potatoes tolerate shade up to 26% even in the temperate zone and are able to reach adequate yields.

3.3. Quality Parameters of Tubers

With regard to the tuber fraction, an increased proportion of undersized tubers was found up until 26% shade (Table 5). Under 50% shade the share of undersized potatoes (<30 mm) decreased insignificantly. The table fraction (30–60 mm) also showed an insignificant increase at higher shade levels. The 50% treatment had a share of 83.90%, while the control only had 74.83%. An insignificant decreasing share with increasing shade was observed for the oversized fraction (>60 mm). The literature indicates that tuber fractions are generally determined by numerous factors, but these do not include light or shade [66].

Table 5. Mean of starch content (% DM), fractions of undersized (<30 mm), table sized (30–60 mm) and oversized tubers (>60 mm) (%), the black spot bruise index (BSB, %) and the macronutrient content of N, P, K, Ca, Mg and S (% DM) for the different shade levels (0%, 12%, 26% and 50%) averaged over the three experiment years. SEM gives the standard error of means.

	Starch	Fraction [O]			BSB	N	P	K	Ca	Mg	S
Shade		**Undersized**	**Table**	**Oversized**							
0%	70.45	4.39	74.83	19.18	16.80	1.30	0.21	2.62	0.03	0.13	0.19
12%	71.04	4.69	77.27	17.06	19.81	1.31	0.22	2.65	0.03	0.13	0.19
26%	70.06	7.84	76.48	12.62	19.70 [□]	1.36	0.22	2.70	0.03	0.13	0.18
50%	68.43	5.62	83.90	8.86	26.65	1.42	0.23	2.69	0.03	0.13	0.19
SEM	0.67	2.60	4.997	4.02	3.82 [□]	0.05	0.01	0.07	0.00 [‡]	0.00 [‡]	0.01
					***p*-values [$]**						
Year	0.043	0.034	0.071	0.011	0.157	0.066	<0.0001	0.011	<0.0001	0.026	0.055
Shade	0.063	0.806	0.642	0.415	0.386	0.339	0.448	0.864	0.808	0.921	0.853
Year x Replicate	0.424	0.705	0.234	0.028	0.011	0.206	0.299	0.287	0.104	0.043	0.138

[O] Data available for 2016 and 2017 only. [□] SEM for 26% shade ± 3.89% due to missing value. [‡] Note: The SEM was between 0 and 0.005, so rounding to two decimal places resulted in a SEM of zero. [$] *p*-value for the global F-test of the corresponding factor.

The tuber size is mainly influenced by the size of the seed tubers and the growing conditions during the growth of the seed tubers. The number of tubers m^{-2} will be determined by the number of formed stolons per stem. It has been shown that irradiance has no effect on this parameter. It is more sensitive to seed size, number of stems, temperature and drought. Studies by Tekalign and Hammes showed that the cultivar also has an influence on the number of tubers. They showed that the fruit or berry development affects the total and marketable tuber mass and the final tuber yield [87,88]. Berries have an influence on the sink-distribution, leading to yield decreases at higher berry numbers.

Hence, tuber size distribution can be influenced by total tuber yield, seeding rate and size of seed tubers, and the number of stems per plant [66]. As mentioned above, older tubers produce more stems than younger tubers. The tuber size distribution is mainly determined by the date of initiation, position and size of the stolon [61]. This shows that shade has no influence on tuber fraction. A study by Knowles and Knowles showed that under the climate conditions of higher northern latitudes, less tubers are formed, but the number of formed tubers of marketable size are higher than for potatoes grown at lower northern latitudes [89]. More potatoes per plant were formed; however, they are smaller, which ultimately led to lower yields. Other experiments have shown that a late harvest results in a larger range of tuber sizes. No additional tubers will grow, but small tubers continue to grow in the later stages of the growing season, resulting in the larger fraction for tuber size [61].

For most potato cultivars (being determinate), the vegetative plant growth ends with flowering when maximum above-ground biomass has formed [32–34]. During flowering, the tuber formation is completed and the potato plant begins to reallocate the sugars from the above-ground parts to the tubers, where starch is formed. After this, only the tuber mass increases and the quality of the tuber changes. The maximum starch yield can be found when half of the leaves are dead and stems begin to die [74]. Due to the simultaneous harvesting in all shade treatments (date determined after the 0% shade treatment) and the delay in ripening (days from senescence initiation to harvest, Table 3) in 2016, the potatoes had less time to reallocate their sugars from leaves to tubers and build up starch. While the effect of the year ($p = 0.043$) was significant, the effect of the shading treatment was not ($p = 0.063$). So, the year should show a statistical difference. A weather-induced delay in development increased the share of smaller tubers in comparison to larger tubers. Smaller tubers have a lower sink demand for sugars that are reallocated from leaves and stored as starch in tubers. This explains the year effect on the starch content. Across years, the starch content showed no significant differences between the shade levels and the unshaded control. An experiment with 34% and 57% shaded tomatoes (*Solanum lycopersicum* L.) showed that there was no influence on glucose by different levels of irradiance [88]. Other studies with shaded tomatoes showed that shade had no influence on final sugar content [89]. This suggests that the starch content in potatoes is also not affected by shade.

Across years, no effect on black spot bruise (BSB) was detectable. None of the macronutrients showed significant treatment effects across years (Table 5) and values were in the given range of values reported in the literature [90].

The above results showed that the influence of shade on plant growth and tuber yield depends on total solar irradiance but also on other factors (e.g., cultivar, soil temperature, and soil moisture). To minimize the shade, which is a controllable effect, different management techniques can be used. If the trees are still small in the first years of an AFS and need grow first, there will be little or no shade influence on the understory crop in the first years. To obtain high yields, potatoes can be integrated in an AFS in the first years without yield reduction. In addition, a large distance between the single trees, the pruning of the trees, the direction of tree strips from north-to-south and the choice of trees with thinner crowns can keep the shade influence at a minimum. Additionally, shade does not remain static on the field during the whole growing period (as in our experimental setup). In a real AFS, the shading varies during the day and moves on a parabolic shape over the crop as the solar position changes, so, the influence of shade in a real AFS can be regarded as smaller than in our experimental setup.

3.4. Prospects for AFS: Potential Total Solar Irradiance in the Temperate Zone of North-European Latitudes

Theoretically, potatoes need an average total irradiation of 14.86 MJ m^{-2} day^{-1} to reach the given light saturation point of 400 μmol m^{-2} s^{-1} PAR to maximize yields. To reach this light saturation under shading, the required total irradiance would amount to 16.89 MJ m^{-2} day^{-1} at 12% shading, 20.08 MJ m^{-2} day^{-1} under 26% shade and 29.72 MJ m^{-2} day^{-1} under 50% shade. Figure 4 shows the hypothetical growing regions in Europe with an assumed limited available irradiance, taking mean total solar irradiance data from 1984–2013 into account [30]. Under a generalized, assumed potato growing season in Europe (30° N, 20° W to 75° N, 40° E) from 1 March to 31 October (DOY 60–304) and without taking any other climatic growth factors except for irradiance into account, potato cultivation under 50% shade would be possible up to 35° N without yield losses (Figure 4). For 26% shade, cultivation would theoretically be possible from 35° to 45° N, for 12% shade from 45° to 55° N, and from 55° to the northern polar circle at 66° N, which is the geographical limit of potato cultivation. In years with high total solar irradiance, the borders for cultivation under shade will shift to the north, while in years with lower irradiance levels the borders will shift to the south. Possible reasons for this shift include less clouds, low variation in the inclination of the earth's axis, high solar activity, low air pollution or weather phenomena (e.g., fog) or depending on the elevation of the potato cultivation site (in higher elevations, a greater amount of total solar irradiance reaches the surface).

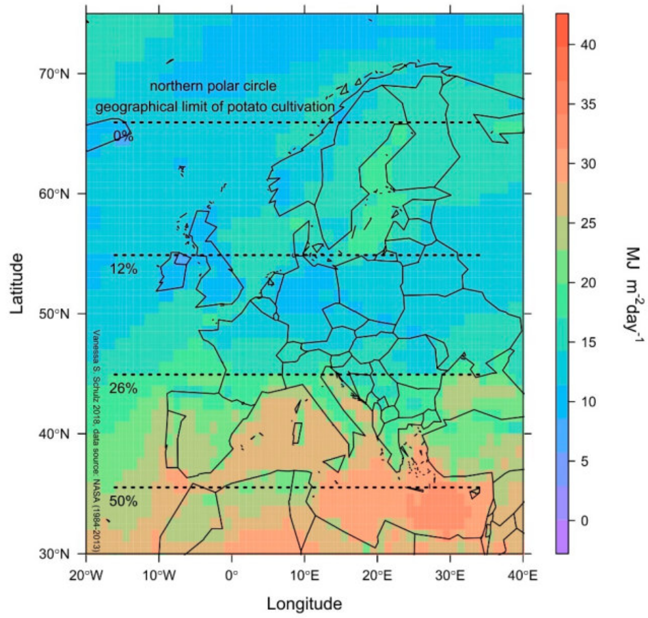

Figure 4. Total solar irradiance (MJ m^{-2} day^{-1}) during the potential potato growing season in Europe (01 March–31 October, 1984–2013) and the theoretical limits of cultivation under shade values of 0%, 12%, 26% and 50% (0.5 × 0.5 m grid, data source NASA [91]).

4. Conclusions

Potatoes are known as being a shade tolerant crop. The results of this study indicated that the DMY was only significantly reduced in 50% shade in years with high irradiance, while a significant reduction at a shade level of 26% only occurred in years with low irradiance. Shading had no significant influence on starch content. Other quality parameters were also not significantly influenced by shade. Yield determining factors like the number of plants per hectare, number of stems per plant, number of tubers per plant and tuber mass per plant were slightly affected by shade. As long as shade is the only influencing factor and no below-ground factors, such as competition for water and nutrients occur, potatoes can be cultivated at latitudes lower than 35° N under 50% shade, while with every increase of 10° N the accepted shade levels have to be halved. Therefore, potatoes can be recommended as an understory crop in AFS up to a shading level of 26% without significant yield and quality reductions under the given total solar irradiance in Southwestern Germany. However, depending on the year (low-irradiance or high-irradiance), this can shift latitudinally in one direction or the other.

Author Contributions: Conceptualization, K.S.; methodology, V.S.S., S.M. and K.S.; software, V.S.S and J.H.; validation, V.S.S. S.M., J.H. and S.G.-H.; formal analysis, V.S.S., S.M. and S.G.H.; investigation, V.S.S.; data curation, V.S.S; writing—original draft preparation, V.S.S., S.M. and S.G.-H.; writing—review and editing, V.S.S., S.M., J.H. and S.G.-H.; supervision, S.G.-H.; project administration, V.S.S, S.M. and S.W.; funding acquisition, K.S.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Date, product, trade name, amount and active ingredients of plant protection agent and also the Mode of Action (MoA) after HRAC (Herbicide Resistance Action Committee), FRAC (Fungicide Resistance Action Committee) and IRAC (Insecticide Resistance Action Committee) for all three years.

Date	Product	Trade Name	Amount and Active Ingredient	MoA
		2015		
18 May	H	2.0 kg ha^{-1} Artist (Bayer AG)	240 g kg^{-1} *flufenacet*, 175 g kg^{-1} *metribuzin*	K3 C1
10 June	F	2.0 kg ha^{-1} Ridomil Gold (Syngenta AG)	40 g kg^{-1} *metalaxyl*-M, 640 g kg^{-1} *mancozeb*	A1 M3
10 June	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
25 June	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
10 July	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
10 July	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
24 July	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
6 August	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
		2016		
6 May	H	3 L ha^{-1} Boxer (Syngenta AG)	800 g L^{-1} *prosulfocarb*	N
6 May	H	0.3 kg ha^{-1} Sencor WG (Syngenta AG)	700 g kg^{-1} *metribuzin*	C1
2 June	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
20 June	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
28 June	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
28 June	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
8 July	F	1.5 L ha^{-1} Infinito (Bayer SE)	62.5 g L^{-1} *fluopicolide*, 625,0 g L^{-1} *propamocarb*-HCl	B5 F4
15 July	F	1.6 L ha^{-1} Infinito (Bayer SE)	62.5 g L^{-1} *fluopicolide*, 625.0 g L^{-1} *propamocarb*-HCl	B5 F4
15 July	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
3 August	H	0.8 L ha^{-1} Quickdown (Ceminova Deutschland GmbH & Co. KG)	24.2 g L^{-1} *pyraflufen*	E14
3 August	H	2 L ha^{-1} Toil (Ceminova Deutschland GmbH & Co. KG)	836 g L^{-1} rapeseed oil methyl ester	
		2017		
5 May	H	2.0 kg ha^{-1} Artist (Bayer AG)	240 g kg^{-1} *flufenacet*, 175 g kg^{-1} *metribuzin*	K3 C1
2 June	F	2.0 kg ha^{-1} Ridomil Gold (Syngenta AG)	40 g kg^{-1} *metalaxyl*-M, 640 g kg^{-1} *mancozeb*	A1 M3
2 June	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
16 June	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
16 June	I	0.3 L ha^{-1} Biscaya (Bayer AG)	240 g L^{-1} *thiacloprid*	4A
5 July	I	0.06 L ha^{-1} Coragen (DuPont)	200 g L^{-1} *chlorantraniliprole*	28
5 July	F	2 kg ha^{-1} Acrobat Plus WG (BASF SE)	90 g kg^{-1} *dimethomorph*, 600 g kg^{-1} *mancozeb*	H5 M3
9 August	H	2.5 L ha^{-1} Reglone (Syngenta AG)	374 g L^{-1} *diquat dibromide*	D

H herbicide, F fungicide, I insecticide.

References

1. Horwith, B. A role for intercropping in modern agriculture. *BioScience* **1985**, *35*, 286–291. [CrossRef]
2. Power, J.F.; Follett, R.F. Monoculture. *Sci. Am.* **1987**, *256*, 78–87. [CrossRef]
3. Gliessman, S.R. Multiple cropping systems: A basis for developing an alternative agriculture. In *US Congress Off Ice of Technology Assessment. Innovative Biological Technologies for Lesser Developed Countries: Workshop Proceedings*; Congress of the USA: Washington, DC, USA, 1985; pp. 69–83.

4. Thevathasan, N.V.; Gordon, A.M.; Simpson, J.A.; Reynolds, P.E.; Price, G.; Zhang, P. Biophysical and ecological interactions in a temperate tree-based intercropping system. *J. Crop Improv.* **2004**, *12*, 339–363. [CrossRef]
5. Kremen, C.; Miles, A. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecol. Soc.* **2012**, *17*. [CrossRef]
6. Nair, P.R. The coming of age of agroforestry. *J. Sci. Food Agric.* **2007**, *87*, 1613–1619. [CrossRef]
7. Nair, P.R. Classification of agroforestry systems. *Agrofor. Syst.* **1985**, *3*, 97–128. [CrossRef]
8. Raintree, J.B. Agroforestry pathways: Land tenure, shifting cultivation and sustainable agriculture. *Unasylva* **1986**, *38*, 2–15.
9. Nair, P.R. *An Introduction to Agroforestry*; Springer Science & Business Media: Berlin, Germany, 1993.
10. Vandermeer, J.H. *The Ecology of Intercropping*; Cambridge University Press: Cambridge, UK, 1992.
11. Montagnini, F.; Nair, P.K.R. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agrofor. Syst.* **2004**, *61*, 281–295.
12. Rigueiro-Rodríguez, A.; Fernández-Núñez, E.; González-Hernández, P.; McAdam, J.H.; Mosquera-Losada, M.R. Agroforestry systems in Europe: Productive, ecological and social perspectives. In *Agroforestry in Europe*; Springer: Berlin/Heidelberg, Germany, 2009; pp. 43–65.
13. Roces-Diaz, J.V.; Rolo, V.; Kay, S.; Moreno, G.; Szerencsits, E.; Fagerholm, N.; Plieninger, T.; Torralba, M.; Graves, A.; Giannitsopoulos, M.; et al. Exploring the Relationships among Bio-Physical and Socio-Cultural Ecosystem Services of Agroforestry Systems across Europe. In Proceedings of the Agroforestry as Sustainable Land Use, Nijmegen, The Netherlands, 28–30 May 2018; EURAF: Nijmegen, The Netherlands, 2018.
14. Elevitch, C.; Mazaroli, D.; Ragone, D. Agroforestry standards for regenerative agriculture. *Sustainability* **2018**, *10*, 3337. [CrossRef]
15. Gao, L.; Xu, H.; Bi, H.; Xi, W.; Bao, B.; Wang, X.; Bi, C.; Chang, Y. Intercropping competition between apple trees and crops in agroforestry systems on the Loess Plateau of China. *PLoS ONE* **2013**, *8*, e70739. [CrossRef]
16. Zhang, W.; Ahanbieke, P.; Wang, B.J.; Xu, W.L.; Li, L.H.; Christie, P.; Li, L. Root distribution and interactions in jujube tree/wheat agroforestry system. *Agrofor. Syst.* **2013**, *87*, 929–939. [CrossRef]
17. Newman, S.M.; Bennett, K.; Wu, Y. Performance of maize, beans and ginger as intercrops in Paulownia plantations in China. *Agrofor. Syst.* **1997**, *39*, 23–30. [CrossRef]
18. Khybri, M.L.; Gupta, R.K.; Ram, S.; Tomar, H.P.S. Crop yields of rice and wheat grown in rotation as intercrops with three tree species in the outer hills of Western Himalaya. *Agrofor. Syst.* **1992**, *17*, 193–204. [CrossRef]
19. Ceccon, E. Production of bioenergy on small farms: A two-year agroforestry experiment using Eucalyptus urophylla intercropped with rice and beans in Minas Gerais, Brazil. *New For.* **2008**, *35*, 285–298. [CrossRef]
20. Friday, J.B.; Fownes, J.H. Competition for light between hedgerows and maize in an alley cropping system in Hawaii, USA. *Agrofor. Syst.* **2002**, *55*, 125–137. [CrossRef]
21. Rahman, M.; Bari, M.; Rahman, M.; Ginnah, M.; Rahman, M. Screening of Potato Varieties under Litchi Based Agroforestry System. *Am. J. Exp. Agric.* **2016**, *14*, 1–10. [CrossRef]
22. Mariana, M.; Hamdani, J.S. Growth and yield of Solanum tuberosum at medium plain with application of paclobutrazol and paranet shade. *Agric. Agric. Sci. Procedia* **2016**, *9*, 26–30. [CrossRef]
23. Pleijel, H.; Danielsson, H.; Vandermeiren, K.; Blum, C.; Colls, J.; Ojanperä, K. Stomatal conductance and ozone exposure in relation to potato tuber yield—Results from the European CHIP Programme. *Eur. J. Agron.* **2002**, *17*, 303–317. [CrossRef]
24. Kareem, I.A. Rattle Tree (ALBIZIA LEBBECK) Effects on Soil Properties and Productivity of Irish Potato (SOLANUM TOBEROSUM) on The Jos Plateau, Nigeria. Ph.D. Thesis, Environmental Resource Planning, University of Jos, Jos, Nigeria, 2007.
25. Nadir, S.W.; Ng'etich, W.K.; Kebeney, S.J. Performance of crops under Eucalyptus tree-crop mixtures and its potential for adoption in agroforestry systems. *Aust. J. Crop Sci.* **2018**, *12*, 1231. [CrossRef]
26. Li, L.; Ljung, K.; Breton, G.; Schmitz, R.J.; Pruneda-Paz, J.; Cowing-Zitron, C.; Cole, B.J.; Ivans, L.J.; Pedmale, U.V.; Jung, H.-S.; et al. Linking photoreceptor excitation to changes in plant architecture. *Genes Dev.* **2012**, *26*, 785–790. [CrossRef]
27. Abdrabbo, M.A.; Farag, A.A.; Abul-Soud, M. The intercropping effect on potato under net house as adaption procedure of climate change impacts. *Appl. Res.* **2013**, *5*, 48–60.

28. Gawronska, H.; Dwelle, R.B.; Pavek, J.J. Partitioning of photoassimilates by potato plants (*Solanum tuberosum* L.) as influenced by irradiance: II. Partitioning patterns by four clones grown under high and low irradiance1. *Am. J. Potato Res.* **1990**, *67*, 163–176. [CrossRef]
29. Kooman, P.L.; Fahem, M.; Tegera, P.; Haverkort, A.J. Effects of climate on different potato genotypes 2. Dry matter allocation and duration of the growth cycle. *Eur. J. Agron.* **1996**, *5*, 207–217. [CrossRef]
30. NASA Atmospheric Science Data Center. Available online: https://eosweb.larc.nasa.gov/sse/global/text/lat_tilt_radiation (accessed on 24 December 2017).
31. Smith, J.; Pearce, B.D.; Wolfe, M.S. Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renew. Agric. Food Syst.* **2013**, *28*, 80–92. [CrossRef]
32. Barbeau, C.D.; Wilton, M.J.; Oelbermann, M.; Karagatzides, J.D.; Tsuji, L.J. Local food production in a subarctic Indigenous community: The use of willow (Salix spp.) windbreaks to increase the yield of intercropped potatoes (Solanum tuberosum) and bush beans (Phaseolus vulgaris). *Int. J. Agric. Sustain.* **2018**, *16*, 29–39. [CrossRef]
33. Wilton, M.J.; Karagatzides, J.D.; Tsuji, L.J. Nutrient Concentrations of Bush Bean (*Phaseolus vulgaris* L.) and Potato (*Solanum tuberosum* L.) Cultivated in Subarctic Soils Managed with Intercropping and Willow (*Salix* spp.) Agroforestry. *Sustainability* **2017**, *9*, 2294. [CrossRef]
34. BSV Saaten–Blühmischung M2 FAKT Maßnahme E2.1 und E2.2. Available online: https://bsv-saaten.de/bluehmischungen-und-bienenweiden/foerderprogramme-1/fakt-1/naturplus-fakt-m2-zr-100-bluehmischung-m2-fuer-fakt-massnahme-e2-1-und-e2-2.html (accessed on 24 November 2018).
35. Röhrig, M.; Sander, R.; eV Geschäftsstelle, I. Interaktive Online-Beratung mit dem Informationssystem Integrierte Pflanzenproduktion (ISIP). In Proceedings of the GIL Jahrestagung, Potsdam, Germany, 6–8 March 2006; pp. 221–224.
36. Bundesministerium für Ernährung. *Landwirtschaft und Verbraucherschutz (BMELV). Gute fachliche Praxis im Pflanzenschutz-Grundsätze für die Durchführung*; BMELV: Bonn, Germany, 2010.
37. Janssen, W. Online irrigation service for fruit and vegetable crops at farmers site. In Proceedings of the 9th EMS Annual Meeting, 9th European Conference on Applications of Meteorology (ECAM) Abstracts, Toulouse, France, 28 September–2 October 2009; Available online: http://meetings.copernicus.org/ems2009/ (accessed on 5 September 2017).
38. Hack, H.; Gall, H.; Klemke, T.H.; Klose, R.; Meier, U.; Stauss, R.; Witzenberger, A. The BBCH scale for phenological growth stages of potato (*Solanum tuberosum* L.). In Proceedings of the 12th Annual Congress of the European Association for Potato Research, Paris, France, 1993; pp. 153–154.
39. Schulz, V.S.; Munz, S.; Stolzenburg, K.; Hartung, J.; Weisenburger, S.; Mastel, K.; Möller, K.; Claupein, W.; Graeff-Hönninger, S. Biomass and Biogas Yield of Maize (*Zea mays* L.) Grown under Artificial Shading. *Agriculture* **2018**, *8*, 178. [CrossRef]
40. Mushagalusa, G.N.; Ledent, J.-F.; Draye, X. Shoot and root competition in potato/maize intercropping: Effects on growth and yield. *Environ. Exp. Bot.* **2008**, *64*, 180–188. [CrossRef]
41. Bodlaender, K.B.A. *Influence of Temperature, Radiation and Photoperiod on Development and Yield*; Wageningen University: Gelderland, The Netherlands, 1963.
42. Cao, W.; Tibbitts, T.W. Leaf emergence on potato stems in relation to thermal time. *Agron. J.* **1995**, *87*, 474–477. [CrossRef]
43. Sprenger, H.; Rudack, K.; Schudoma, C.; Neumann, A.; Seddig, S.; Peters, R.; Zuther, E.; Kopka, J.; Hincha, D.K.; Walther, D.; et al. Assessment of drought tolerance and its potential yield penalty in potato. *Funct. Plant Biol.* **2015**, *42*, 655–667. [CrossRef]
44. Fernández, S.D.M.; Aguilar, R.M.; Moreno, Y.S.; Pérez, J.E.R.; León, M.T.C.; Saldaña, H.L. Growth and sugar content of potato tubers in four maturity stages under greenhouse conditions. *Rev. Chapingo Ser. Hortic.* **2018**, *24*, 53–67. [CrossRef]
45. McMaster, G.S.; Wilhelm, W.W. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* **1997**, *87*, 291–300. [CrossRef]
46. Bundessortenamt. *Richtlinien für die Durchführung von Landwirtschaftlichen Sortenversuchen*; Bundessortenamt: Hannover, Germany, 2000.
47. Bundessortenamt. *Beschreibende Sortenliste Kartoffel—2017*; Bundessortenamt: Hannover, Germany, 2017.
48. Hoffmann, G. *VDLUFA-Methodenbuch Band I: Die Untersuchung von Boeden*; Loseblattsammlung; VDLUFA-Verlag: Darmstadt, Germany, 1991; ISBN 3-922712-42-8.

49. Janßen, E. *VDLUFA-Methodenbuch Band VII: Umweltanalytik*, 3rd ed.; VDLUFA: Darmstadt, Germany, 2003.
50. Bassler, R. *VDLUFA-Methodenbuch, Band III: Die Chemische Untersuchung von Futtermitteln*; 3. Aufl., 2. Ergänzungslieferung 1988 und 3. Ergänzungslieferung 1993; VDLUFA-Verlag: Darmstadt, Germany, 1988.
51. Amtsblatt, D.E.U. Verordnung (EG) Nr. 152/2009 der Kommission vom 27.01. 2009 zur Festlegung der Probenahmeverfahren und Analysemethoden für die amtliche Untersuchung von Futtermitteln. *L* **2009**, *54*, 130.
52. Heinecke, A. *Beitrag zur Ermittlung der Biochemischen Ursachen der Schwarzfleckigkeit bei Kartoffeln*; Georg-August-Universität Göttingen: Gottingen, Germany, 2007.
53. Baty, F.; Ritz, C.; Charles, S.; Brutsche, M.; Flandrois, J.-P.; Delignette-Muller, M.-L. A toolbox for nonlinear regression in R: The package nlstools. *J. Stat. Softw.* **2015**, *66*, 1–21. [CrossRef]
54. Fox, J. *Nonlinear Regression and Nonlinear Least Squares*; Wiley: New York, NY, USA, 2002.
55. Demagante, A.L.; Zaag, P.V. The response of potato (*Solanum* spp.) to photoperiod and light intensity under high temperatures. *Potato Res.* **1988**, *31*, 73–83. [CrossRef]
56. Sale, P.J.M. Productivity of vegetable crops in a region of high solar input. II. Yields and efficiencies of water use and energy. *Aust. J. Agric. Res.* **1973**, *24*, 751–762. [CrossRef]
57. Kuruppuarachchi, D.S.P. Intercropped potato (*Solanum* spp.): Effect of shade on growth and tuber yield in the northwestern regosol belt of Sri Lanka. *Field Crops Res.* **1990**, *25*, 61–72. [CrossRef]
58. Ebwongu, M.; Adipala, E.; Ssekabembe, C.K.; Kyamanywa, S.; Bhagsari, A.S. Effect of intercropping maize and Solanum potato on yield of the component crops in central Uganda. *Afr. Crop Sci. J.* **2001**, *9*, 83–96. [CrossRef]
59. Menzel, C.M. Tuberization in potato at high temperatures: Interaction between temperature and irradiance. *Ann. Bot.* **1985**, *55*, 35–39. [CrossRef]
60. Struik, P.C.; Vreugdenhil, D.; Haverkort, A.J.; Bus, C.B.; Dankert, R. Possible mechanisms of size hierarchy among tubers on one stem of a potato (*Solanum tuberosum* L.) plant. *Potato Res.* **1991**, *34*, 187–203. [CrossRef]
61. Abu-Zinada, I.A.; Mousa, W.A. Growth and productivity of different potato varieties under Gaza Strip conditions. *Int. J. Agric. Crop Sci.* **2015**, *8*, 433.
62. Stamm, P.; Kumar, P.P. The phytohormone signal network regulating elongation growth during shade avoidance. *J. Exp. Bot.* **2010**, *61*, 2889–2903. [CrossRef] [PubMed]
63. Arsenault, W.J.; LeBlanc, D.A.; Tai, G.C.; Boswall, P. Effects of nitrogen application and seedpiece spacing on yield and tuber size distribution in eight potato cultivars. *Am. J. Potato Res.* **2001**, *78*, 301–309. [CrossRef]
64. Putz, B. *Kartoffeln: Züchtung, Anbau, Verwertung*; Behr's Verlag: Hamburg, Germany, 1989.
65. Struik, P.C.; Haverkort, A.J.; Vreugdenhil, D.; Bus, C.B.; Dankert, R. Manipulation of tuber-size distribution of a potato crop. *Potato Res.* **1990**, *33*, 417–432. [CrossRef]
66. Delaplace, P.; Brostaux, Y.; Fauconnier, M.-L.; du Jardin, P. Potato (*Solanum tuberosum* L.) tuber physiological age index is a valid reference frame in postharvest ageing studies. *Postharvest Biol. Technol.* **2008**, *50*, 103–106. [CrossRef]
67. O'Brien, P.J.; Firman, D.M.; Allen, E.J. Effects of shading and seed tuber spacing on initiation and number of tubers in potato crops (Solanum tuberosum). *J. Agric. Sci.* **1998**, *130*, 431–449. [CrossRef]
68. de Lucas, M.; Davière, J.-M.; Rodríguez-Falcón, M.; Pontin, M.; Iglesias-Pedraz, J.M.; Lorrain, S.; Fankhauser, C.; Blázquez, M.A.; Titarenko, E.; Prat, S. A molecular framework for light and gibberellin control of cell elongation. *Nature* **2008**, *451*, 480. [CrossRef]
69. Sun, T. Gibberellin-GID1-DELLA: A Pivotal Regulatory Module for Plant Growth and Development. *Plant Physiol.* **2010**, *154*, 567–570. [CrossRef]
70. García-Martinez, J.L.; Gil, J. Light regulation of gibberellin biosynthesis and mode of action. *J. Plant Growth Regul.* **2001**, *20*, 354–368. [CrossRef]
71. Kamiya, Y.; García-Martínez, J.L. Regulation of gibberellin biosynthesis by light. *Curr. Opin. Plant Biol.* **1999**, *2*, 398–403. [CrossRef]
72. Wurr, D.C.E.; Hole, C.C.; Fellows, J.R.; Milling, J.; Lynn, J.R.; O'Brien, P.J. The effect of some environmental factors on potato tuber numbers. *Potato Res.* **1997**, *40*, 297–306. [CrossRef]
73. Kolbe, H.; Stephan-Beckmann, S. Development, growth and chemical composition of the potato crop (*Solanum tuberosum* L.). II. Tuber and whole plant. *Potato Res.* **1997**, *40*, 135–153. [CrossRef]
74. Ewing, E.E.; Wareing, P.F. Shoot, Stolon, and Tuber Formation on Potato (*Solanum tuberosum* L.) Cuttings in Response to Photoperiod. *Plant Physiol.* **1978**, *61*, 348–353. [CrossRef] [PubMed]

75. Pohjakalli, O. On the effect of the intensity of light and length of day on the energy economy of certain cultivated plants. *Acta Agric. Scand.* **1950**, *1*, 153–175. [CrossRef]
76. Saha, R.R.; Sarker, A.Z.; Talukder, A.H.M.M.R.; Akter, S.; Golder, P.C. Variability in Growth and Yield of Potato Varieties at Different Locations of Bangladesh. *Bangladesh Soc. Hortic. Sci.* **2016**, *2*, 101–110.
77. Hébert, Y.; Guingo, E.; Loudet, O. The Response of Root/Shoot Partitioning and Root Morphology to Light Reduction in Maize Genotypes. *Crop Sci.* **2001**, *41*, 363–371. [CrossRef]
78. Geigenberger, P.; Kolbe, A.; Tiessen, A. Redox regulation of carbon storage and partitioning in response to light and sugars. *J. Exp. Bot.* **2005**, *56*, 1469–1479. [CrossRef]
79. Manrique, L.A.; Kinry, J.R.; Hodges, T.; Axness, D.S. Dry Matter Production and Radiation Interception of Potato. *Crop Sci.* **1991**, *31*, 1044–1049. [CrossRef]
80. Dam, J.V.; Kooman, P.L.; Struik, P.C. Effects of temperature and photoperiod on early growth and final number of tubers in potato (*Solanum tuberosum* L.). *Potato Res.* **1996**, *39*, 51–62.
81. Streck, N.A.; de Paula, F.L.M.; Bisognin, D.A.; Heldwein, A.B.; Dellai, J. Simulating the development of field grown potato (*Solanum tuberosum* L.). *Agric. For. Meteorol.* **2007**, *142*, 1–11. [CrossRef]
82. Sale, P.J.M. Effect of shading at different times on the growth and yield of the potato. *Aust. J. Agric. Res.* **1976**, *27*, 557–566. [CrossRef]
83. Loewe, V.; Delard, C. Stone pine (Pinus pinea L.): An interesting species for agroforestry in Chile. *Agrofor. Syst.* **2019**, *93*, 703–713. [CrossRef]
84. Tekalign, T.; Hammes, P.S. Growth and productivity of potato as influenced by cultivar and reproductive growth—I. Stomatal conductance, rate of transpiration, net photosynthesis, and dry matter production and allocation. *Sci. Hortic.* **2005**, *105*, 13–27. [CrossRef]
85. Tekalign, T.; Hammes, P.S. Growth and productivity of potato as influenced by cultivar and reproductive growth—II. Growth analysis, tuber yield and quality. *Sci. Hortic.* **2005**, *105*, 29–44. [CrossRef]
86. Knowles, N.R.; Knowles, L.O. Manipulating stem number, tuber set, and yield relationships for northern-and southern-grown potato seed lots. *Crop Sci.* **2006**, *46*, 284–296. [CrossRef]
87. Kolbe, H.; Stephan-Beckmann, S. Development, growth and chemical composition of the potato crop (*Solanum tuberosum* L.). I. leaf and stem. *Potato Res.* **1997**, *40*, 111–129. [CrossRef]
88. Kläring, H.-P.; Krumbein, A. The effect of constraining the intensity of solar radiation on the photosynthesis, growth, yield and product quality of tomato. *J. Agron. Crop Sci.* **2013**, *199*, 351–359. [CrossRef]
89. Gautier, H.; Diakou-Verdin, V.; Bénard, C.; Reich, M.; Buret, M.; Bourgaud, F.; Poëssel, J.L.; Caris-Veyrat, C.; Génard, M. How does tomato quality (sugar, acid, and nutritional quality) vary with ripening stage, temperature, and irradiance? *J. Agric. Food Chem.* **2008**, *56*, 1241–1250. [CrossRef] [PubMed]
90. Burlingame, B.; Mouillé, B.; Charrondière, R. Nutrients, bioactive non-nutrients and anti-nutrients in potatoes. *J. Food Compos. Anal.* **2009**, *22*, 494–502. [CrossRef]
91. NASA POWER Data Access Viewer. Available online: https://power.larc.nasa.gov/data-access-viewer/ (accessed on 1 November 2018).

6 General Discussion

Different aspects of trees on arable land were discussed in the previous **Chapters I – III**. All results have been published in scientific peer-review journals. Every journal article contains a detailed discussion. Therefore, this General Discussion focus on aspects, which go beyond the already discussed parts and extends the overall context of the investigated aspects.

The focus of **Chapter I** is on yield performance and mortality of willows for SRC under different combinations of tillage and weed management as alternative establishment methods. This chapter did not in depth discuss the issue, if yields might change due to differences in the used mode of actions of the plant protection agents or due to the shift of the weed seed bank by the different tillage systems. This will be discussed in **Chapter 6.2 Alternative establishment methods of SRC**. In a combined cultivation of trees and agricultural crops, trees affect the crops in many ways, but the most prominent factor is shade. There are various agricultural crops, which could not all be tested for their suitability for cultivation under shady conditions. **Chapter II** and **III** only focused on the shade-intolerant C4 plant maize and the shade-tolerant C3 plant potato. Therefore, in **Chapter 6.3 Shading tolerance of crops**, literature will be reviewed, giving an overview on other world-wide important crops, which can be considered for cultivation under shade. In an AFS, there are a variety of factors that influence crop growth. In **Chapter II** and **III**, only light was focused as influence factor. Therefore, in **Chapter 6.4 Above- and below-ground interaction** the factors water and nutrient competition will be considered. The overall economic performance is of great importance to the farmers, who will manage an AFS. In **Chapter 6.5 Economic performance,** a model AFS is used to compare the profits of sole-cropping maize and potato with intercropping maize and potato in a strip-wise cultivation of SRC for energy production and strips for the production of high-valuable timber. The environmental and biodiversity benefits of an AFS have been mentioned only peripherally in the peer-reviewed articles, but have not been considered in detail. **Chapter 6.6 Environmental performance** deals with this topic. Finally, in **Chapter 6.7 Further research** approaches will be addressed.

6.1 Experimental Results

Trees represent a special challenge on agricultural land. Thorough planting and caretaking are important for a profitable system. Thus, **Chapter I** was designed to investigate different establishment methods for an SRC, including willows. The idea was, that willows for SRC need a successful establishment phase due to their sensitivity to weed competition in their youth. An appropriate combination of soil tillage and weed management leads to a successful establishment and, thus, high yields. Therefore, the effects of three different tillage systems (mouldboard plough, chisel plough + ley crop, no-till) and the effects of eight different weed management systems (chemical, chemical + mechanical, mechanical) on biomass production of SRC willows were investigated to determine the ideal combination of tillage and weed management, which generates the highest amount of biomass and yields. It could be shown, that other tillage systems than the recommended ploughing and secondary tillage, can offer promising alternatives. The implemented weed management system depends on the practiced tillage system. While the combination of mouldboard plough and a broad application of herbicides reached a yield of almost of 14 Mg ha^{-1} dry matter, the same herbicide treatment reached almost half of the yield under chisel ploughing. In general, chisel ploughing with a ley crop averaged the lowest yields. The ley crop seems to lead to higher competition. Under no-till almost all weed management treatments showed promising yields, except of band-spraying within and mulching between willow rows.

Chapter II and **III** investigated the shade-tolerance of maize and potato. Maize, as a shade-intolerant plant, grown under different shading levels (12 %, 26 % and 50 %), showed reduced growth, lower yields and smaller biogas outputs than unshaded plants. It could be proven, that plant height and LAI were reduced, which was later reflected in the reduction of dry matter, biogas and methane yields. 50 % shading reduced yields about almost the half, wherefore the cultivation of silage maize cannot be recommended at shade levels higher than 26 %. On the other hand, the shade-tolerant crop potato, grown in the bottom layer of tropical and subtropical intercropping systems, showed no negative effects in growth and yield. Under central European solar irradiance there is less information available on growth, yield and quality performance of shaded potatoes. Therefore, the objectives were to evaluate the impact of the different shading levels (12 %, 26 % and 50 %) on potato growth, tuber yield and quality parameters under the given solar irradiance of southwest Germany. Significant growth changes occurred at 50 % shading. Depending on the year, tuber dry matter yield showed a decrease of 19-44 % at 50 % shade, while starch content showed no significant differences under shade, compared to the unshaded treatment. Overall, potato seems to tolerate shading and can therefore be integrated in an AFS, coping with a reduced solar irradiance up to 26 %.

6.2 Alternative establishment methods of SRC

As already mentioned, the recommended establishment combination for a SRC is ploughing in autumn and secondary tillage prior planting, followed by a pre-emergence herbicide application immediately after planting (Möller et al., 2007). However, especially for areas where reduced tillage is required due to erosion or evaporation control, other forms of soil management can be of interest (chisel ploughing + ley crop or no-till). Up to this point, only a broadcast application of herbicides has been considered for weed management. For reasons of chemical plant protection reduction in the context of biodiversity protection, a band spraying within and mechanical weed control between willow rows can be an interesting alternative. **Chapter I** discussed the effects of the various combinations. Both, tillage and weed management proved to be important for growth and final yields of willows. The results showed, that the treatments had different effects on willow growth and yield. However, the results also indicated that some weed treatments worked better in specific tillage systems, than others. This can be attributed to the shift of the weed seed bank in the soil layers by tillage. Other aspects which affected the weed seed bank are the mode of action of the used herbicides. These aspects will be discussed in more detail in the following section.

In case of the different tillage systems, it is characteristic that mouldboard ploughing transferred seeds from shallower to deeper soil layers. Mouldboard plough is known as a good treatment against grasses. Studies found less weed seeds in mouldboard ploughed sites, than in sites with chisel plough or no-till (Feldman et al., 1997). For chisel ploughing and no-till more seeds in the cultivated upper layers could be found. No-till leads to more than 60 % weed emergence (Bàrberi and Cascio, 2001). It has also been shown that, especially under no-till, the weed seed bank and weed infestation increases (Légère et al., 2011). Since the soil is only loosened and not turned when chisel ploughed, there is no exchange of soil seeds between the different soil layers. Therefore, and by the sowing of a ley crop, less weeds can occur. The data on weed covered area in **Chapter I** proved the fact, that the different soil tillage systems led to different amounts of seeds in the soil seed bank. While in all mouldboard plough and no-till treatments the weed-covered area was near or higher 60 %, under chisel plough with a ley crop the highest percentage of weed-covered area was 55 %. This indicated that, if a ley crop develops faster than the weeds and covers bare soil, the ley crop is able to suppress weeds due to an additional soil coverage. Further, the results showed a higher weed coverage in the mouldboard plough treatments compared to the chisel plough treatment. However, this effect was masked by the fact that, in the chisel plough plots only broadleaved weeds were counted. A separation between grass weeds and the ley crop would have been too complex. When mouldboard ploughing, the weed seeds are shifted from the upper soil layers to deeper layers, which have poorer germination conditions and, thus, inhibit or prevent the germination of weeds (Rahman et al., 2000; Roger-Estrade et al., 2001). Under no-till the absence of soil preparation allows only the weeds in upper soil layers to germinate. This indicates that every tillage treatment needs an adequate weed treatment to have a successful willow SRC.

The widely recommended herbicide combination (0) of Terano (*Metosulam* and *Flufenacet*) and Stomp (*Pendimethalin*) at pre-emergence and Fusilade Max (*Fluazifop-p-butyl*) and Lontrel 100 (*Clopyralid*) at post-emergence covers a wide range of weeds through its active ingredients and, thus, reaches almost all kind of weeds (**Table 1**). It was shown in **Chapter I** that this treatment had the highest yields under mouldboard ploughing and in the chisel plough treatment. During pre-emergence, seedling root growth is inhibited by the herbicides, while in post-emergence grasses are controlled via ACCase inhibitors and broadleaves via growth regulators. From the view of biodiversity, herbicide-intensive post-emergence treatments must be seen critically, as weeds can serve as food sources and habitats, for a large number of arthropods, after their emergence. Alternative (1) uses the same mode of action during pre-emergence as in the common herbicide combination (0), but in post-emergence grasses and broadleaves are only controlled via ALS inhibitors by one herbicide. This can be problematic; if weeds develop in post-emergence that cannot be attracted and killed via ALS inhibitors. Alternative (2), a combination of one herbicide in pre-emergence (Sencor WG; *Metribuzin*) and one in post-emergence (Kontakt 320 SC; *Phenmedipham*), only uses one agent per application. Both plant protection agents are based on the inhibition of Photosynthesis System II, while in post-emergence there is no more control of grasses by the used herbicide. The disadvantage of this treatment is, that green leaf mass must be present at the time of application so the herbicide can attract the weed. Therefore, weeds must have emerged and, thus, already compete with the willows. More problems, however, results from the fact, that the same mode of action is used in both, the pre- and post-emergence treatment. This increases the risk of resistance formation. In order to prevent resistances, a change should be made between the mode of actions with different target-sites. First, the danger of resistance formation does not seem to be so high in SRC, since chemical weed control only takes place in the year of establishment. But, if SRC strips should be established between arable crops, this is an effect that should not be ignored, especially if chemical crop protection treatments with the same mode of action should be used on the agricultural land. A proactive planning and adjusted herbicides use in the tree-strips and the crops land is therefore crucial.

Table 1: Application details of the tested herbicide combinations in **Chapter I**. Pre- or post-emergence; 0 (green filled boxes) recommended herbicides, 1 (red filled boxes) herbicide alternative 1, 2 (blue filled boxes) herbicide alternative 2, Trade Names, Active Ingredients, Chemical Family, Mode of Action after HRAC (Herbicide Resistance Action Committee) and WSSA (Weed Science Society of America) and controlled Targets.

	Application 0	Application 1	Application 2	Trade Name	Active Ingredient	Chemical Family	HRAC	WSSA	Target
Pre-emergence	■	■		Terano	*Metosulam*	Triazolopyrimidine	B	2	Broadleaf, Grasses
	■	■			*Flufenacet*	Oxacetamide,	K3	15	
	■	■		Stomp	*Pendimethalin*	Dinitroaniline	K1	3	Broadleaf, Grasses
			■	Sencor WG	*Metribuzin*	Triazinone	C1	5	Broadleaf, Grasses
Post-emergence	■			Fusilade Max	*Fluazifop-p-butyl*	Aryloxyphenoxy-propionate 'FOPs'	A	1	Grasses
	■			Lontrel 100	*Clopyralid*	Pyridine carboxylic acid	O	4	Broadleaf
		■		Katana	*Flazasulfuron*	Sulfonylurea	B	2	Broadleaf, Grasses
			■	Kontakt 320 SC	*Phenmedipham*	Phenyl-carbamate	C1	5	Broadleaf

A Lipid Synthesis Inhibitors; ACCase Inhibitors
B Amino Acid Synthesis Inhibitors; ALS Inhibitors
C1 Photosynthesis Inhibitors; Photosystem II Inhibitors
K1 Seedling Root Growth Inhibitors; Microtubule Inhibitors
K3 Seedling Root Growth Inhibitors; Long-chain Fatty Acid Inhibitor
O Growth Regulators; specific site unknown

Under mouldboard ploughing broad herbicide application of alternative (1), Katana as post-emergence herbicide, could not be recommended. The use of Katana, an herbicide classified according to Herbicide Resistance Action Committee (HRAC) in class B, in combination with pre-emergence herbicides, which are also partly classified into class B, is not recommended. Pre- and post-emergence herbicides both use ALS inhibitors as mode of action, which have a high risk of developing resistances. Under no-till this effect was not detectable, as it was not under chisel plough + the ley crop. Under these soil tillage systems, the broad herbicide application (2) works well. If the mouldboard plough treatment is assisted by an additional mechanical weed treatment between willow rows, the use of an herbicide roll is not recommended, as only those weeds are reduced that have reached the active working height of the herbicide roll. Smaller weeds are not affected and can develop further. As a result, they are competing with the willow cuttings.

Chisel ploughing with ley crop needs broadband weed treatment. Band spraying within and mechanical treatment between willow rows did not adequately treat the already established ley crop so that the willows could grow without restrains. Under chisel ploughing + ley crop only pure chemical treatments should be applied. In chemical + mechanical treatments the mechanical weed management is only applied between the rows while the chemical treatment is done within the willow row. Therefore, a broad application of herbicides is needed to minimize competition effects. All broad application treatments were able to capture the weed spectrum well. This was probably also due to the competition from the ley crop. There is no risk of decimating the ley crop with a post-emergence grass herbicide (e.g Fusilade Max or Katana). As shown in **Chapter I**, yields from the combination of chisel ploughing and other chemical crop protection were lower, but not significantly lower than those of the recommended practice (mouldboard plough + Terano / Stomp, Fusilade Max / Lontrel 100).

If no-till should be practiced, for reasons of erosion control, fuel saving or evaporation protection, all weed treatments except of herbicide within the rows and mulching between the rows offer possible alternatives.

Once, the site-adapted combination of tillage and weed management is found, SRC do not need further care. However, the farmer must be aware that trees (whether SRC or single high-valuable timber trees) have an impact on the agricultural crops grown below. Shade is the best observable and proven influence. Therefore, even in the first years of an AFS, the understory crop should be carefully chosen.

6.3 Shading tolerance of crops

As shown in **Chapter II** and **III**, some crops are more shade-tolerate (e.g. potato) than others (e.g. maize).
There are numerous other crops besides maize and potato that have already been tested for their suitabilty to be grown under shade. In the following, the world's most important crops will be briefly outlined in terms of their shade-tolerance.

Wheat showed a decreased yield in AFS compared to stands under full sunlight. This yield reduction was attributed to a reduced tiller and head density. Although the plants have higher specific leaf area (SLA), this could not compensate the lower photosynthetically active radiation (PAR) (Sudmeyer and Speijers, 2007). On the other hand, Mu et al. (2010) showed, that shade-influence strongly depends on the used variety. In addition, experiments showed that the timing of shade is also crucial for yield development. While shading during pre-flowering affects the assimilation and thus the number of grains per ear and ears per m^2, during post-flowering the grain growth and thus the 1000-grain weight is affected. If the 1000-grain weight is lowered, yield also reduced. This increase in 1000-grain weight cannot compensate the lower number of grains per ear and ear per m^2. If these yield-determining parameters are reduced due to permanent shading, yields are reduced. This shows that shade affects grain growth more, than assimilate translocation (Wardlaw, 1970; Jenner, 1980; Shanahan et al., 1984; Grabau et al., 1990; Sinclair and Jamieson, 2006; Li et al., 2010). The reduced number of plants per m^2 led to a higher nitrogen availability for fewer plants, thus protein content in grains is higher. Also, a higher soil moisture and faster mineralization can increase protein content (Lin et al., 2001a).

Researches showed that low light intensity will prolong the growing period and increase plant height and leaf area of rice (*Oryza sativa* L.). Before heading, shade reduced the number of ears, after heading it negatively influenced photosynthesis, which results in a reduced number of filled grains and a reduced 1000-grain weight. As already shown for shaded wheat, this will reduce the final grain yield (Liu et al., 2014). Liu et al. (2014) reported a shift from chlorophyll a to b, when rice was grown under shade. Chlorophyll a is needed to transform solar energy in electrochemical energy which is needed for grain production. They also found, that ribulose bisphosphate carboxylase activity is decreased under shade. This enzyme is important for the photosynthetic rate of leaves. Under shade rice plants received more blue-purple (diffuse) light and fewer red light which reduced photosynthesis. Thus, the reproductive organs do not receive enough assimilates from nutrient source organs. Furthermore, shade inhibits the translocation of assimilates. Other studies also showed that there are several other pathways and factors in rice, that are influenced by shade (Jusoff et al., 2013).

During the seed filling period photosynthesis is the main source for energy in soybeans. Shade caused a source-limited yield reduction by a limitation of the carbon and nitrogen assimilation. Under 50 % and 80 % shade, seed number decreased compared to the control, while seed size increased, which could not compensate the grain yield reduction by shade. Shade also decreased N_2-fixation and therefore the available nitrogen for seed growth (Proulx and Naeve, 2009). The protein content of shaded soybeans was higher than in the unshaded control, while oil content decreased. This is attributed to the amount of nitrogen available for less seeds, when compared to the control. Other researchers found, that LAI increased and specific leaf weight decreased with increasing shade (25 %, 65 % and 100 % of full sunlight) under well-watered environmental conditions. Grain yield also decreased, which was seen as a result of a reduced plant membrane stability under shade stress, so the plant invested more storage products in increasing LA, to form a higher photosynthetic surface (Ghassemi-Golezani et al., 2013).

Canola (*Brassica napus* L.) in a valuable-timber AFS in Canada showed a reduced seed oil concentration and seed oil yields up to 4 m distance from tree trunk, compared to a mono-cropped canola stand. Plants, which were grown near the trees, had a higher specific leaf area. This system used a hybrid poplar with a high water demand, so the yield reduction can also be linked to below-ground competition (Beaudette et al., 2010). Another experiment with shaded canola (leaving 40 % of full sunlight) led to reduced pods m^{-2}; while seed pod^{-1} and 1000-grain weight were not affected by shade. Yield was significantly reduced by shade. Less assimilates were formed and so pod set and seed number pod^{-1} were influenced (Habekotté, 1993). A reduced number of pods has also been found by Tayo and Morgan (1979). Under low light conditions (4,000 vs. 28,0000 lm m^{-2}), number of pods $plant^{-1}$ was reduced, influenced by the supply with carbon assimilates, while weight pod^{-1} was higher. Time of shading is important. Shading after anthesis has a greater influence on final yield. A decrease in light decreased the carbon supply, which affected the number of flowers and pods (smaller pods, fewer and lighter seeds) (Tayo and Morgan, 1979).

The yield of shaded *Phaseolus vulgaris* (L.) showed, that even shading at levels of 55 % of full sunlight did not led to significant yield differences compared to the control. Hadi et al. (2006) ascribed it to the significantly increased LAI under shade. Thus, *P. vulgaris* is able to use more light, due to an increased LAI in the shaded treatments. Therefore, comparable yields to the control were reached. The plant produced less grains, but these produced grains had a higher 1000-grain weight (Hadi et al., 2006).

Vicia faba (L.) showed a yield increase with increasing shade. Shade did not affect the grains per plant significantly but increased the 1000-grain weight and affected the final yield. An enlarged leaf area under shade could be observed (Nasrullahzadeh et al., 2007).

Fodder species which can be found in pastures are also affected, when they grow under shade influence by trees. While most of the fodder species used by Lin et al. (2001b) at 0 %, 50 % and 80 % shade showed a decrease in above-ground biomass, crude protein content of the introduced cool-season grasses increased with increasing shade. Acid detergent fiber and neutral detergent fiber were increased or unaffected. They related it to the lower accumulation of sugar and starch in leaves under shady conditions. The higher nitrogen content was ascribed to a faster nitrogen mineralization in moist soil, a faster litter turnover and due to a smaller plant cell size, a concentrating effect. For legume species these effects were not detectable (Lin et al., 2001a). Cole and Cole (2000) showed, that the influence is highly species dependent from one year to another. While some grasses showed an increase in height and width, other grasses showed no influence by shade. They ascribed differences to the climatic variability. A study by Kephart et al. (1992) with different C3 and C4 perennial grasses showed a decrease in specific leaf weight and an increase in leaf area ratio with increasing shade. Yield was positively correlated with decreasing shade. This effect was stronger for C4, than for C3 grasses. Plants under shade produced larger, but thinner leaves.

It has been shown that shade does not increase the yields of the above-mentioned plants, expect from *V. faba*. Either they decrease (e. g wheat, soybean) or remain unchanged (e. g. *P. vulgaris*). However, shade can lead to a change in the quality of harvested material. Thus, light seems to be a highly limiting factor for plant growth, when below-ground interactions are not taken into account. Nevertheless, Sudmeyer and Speijers (2007) stated that water is more limiting than light for plant growth.

6.4 Above- and below-ground interaction

When trees and crops are cultivated together there are various interactions. These interactions can be both, above- and below-ground. **Figure *2*** summarizes the main effects of trees on arable crops.

As major above-ground interactions the competition for light, microclimatic modifications (e.g. decreased temperature and increased humidity), insect density and diversity on the understory culture are discussed (microclimatic effects). As below-ground interaction the competition for water and nutrients, allelopathic effects, hydraulic lift, the uptake of leached nutrients by trees and N_2-fixation by legume trees are observed (root interactions) (Ong et al., 1991; Jose et al., 2004; Smith et al., 2013).

Certainly, there are a lot of other interactions that have not been investigated yet. A close look into the literature suggests the competition for light, water and nutrients as the main effects. **Chapters II** and **III** discussed the influence of reduced solar irradiance conditions caused by trees on crops, while the below-ground interactions were disregarded. Therefore, in this chapter the below-ground competitions between trees and agricultural crops should be considered.

above-ground interactions	
reduced wind speed	→ reduced evaporation → wind erosion control (reduced soil loss)
reduced temperature	→ reduced heat stress by cooler and moisture soil conditions
reduced PAR / shade	→ reduced yields → changes in quality
pest management	→ habitat for predators → greater distance between host plants make it more difficult for the herbivore to find host plant → plants / trees as repellent → more diverse arthropod fauna → refuge for birds and insects
reduced run-off	by grass strips → reduced nutrient removal → nutrient capture function by tree roots
competition for water	→ reduced yields → reduced biomass growth → reduced fertilizer use efficiency
competition for nutrients	→ reduced yields → changes in quality
release of allelochemicals / phytotoxicity	→ reduced germination / plant growth possible (depends on plant species, concentration level of allelochemicals, soil conditions)
'safety net' role	→ uptake of leached nutrients by deeper tree roots and recycling as litterfall and root turnover
hydraulic lift	→ water uptake from deeper soil layers by tree roots and release in upper soil layers → nutrient cycling and water balance
N2 fixation	→ more nitrogen available for crops by atmospheric N2 fixing trees
below-ground interactions	

Figure 2: Possible above and below-ground effects of trees in an agricultural landscape (own figure, based on Jose et al. (2004)).

6.4.1 Water

While some studies found that in maize the competition for light is of higher importance than competition for water (Reynolds et al., 2007), for other experimental sites it was proven, that the influence of water is more important than light (Jose et al., 2000a). **Figure 3** tries to figure out the complex relationships between light, water and nutrient competition on plant growth.
Water, in combination with CO_2 is needed to produce oxygen and carbohydrates which allow plant growth. Water is also needed as transport medium for nutrients and storage substances. If two plants are grown at the same time, on the same area of land, there will be a competition for water. Based on their development stage, crops have different water requirements.
Water stress affects photosynthesis and plant growth. If the plant water uptake is not in equilibrium with the leaf transpiration, the leaf stomata are closed and no further uptake of CO_2 can occur. If the amount of CO_2 is to low, the production of NADPH and ATP is limited and the energy for growth and photosynthesis is reduced (Tezara et al., 1999). Depending on the cultivated agricultural crop, the competition for water may be the more important factor than light, especially for water limited locations.

Selecting the already discussed species of **Chapter II** and **III**, maize has a water requirement of 500 to 800 mm during its whole growing period, while potato has a water requirement of 500 to 700 mm (FAO, 2019). For woody species, a SRC of willows has a water demand of 600 to nearly 2000 mm (Guidi et al., 2008). During the vegetation period sweet cherry trees for high-valuable timber production at the age of 4 to 5-year have a requirement of 700 to 800 mm, a 25 year-old orchard used 760 to 1000 mm (Steduto et al., 2012; Juhász et al., 2013).
At the southwest German location Karlsruhe, where the experiments with maize and potatoes of **Chapter II** and **III** were carried out, 509 mm were the long-time average precipitation during the vegetation period (March to October).
Depending on the root system of the different plants, a strong competition between the plants which accessing the same pool of water occurs.

Maize roots can reach a rooting depth of 1.30 m and the lateral root extension radius is about 0.6 m (Pagès and Pellerin, 1994). The root system of potatoes is mainly concentrated in the upper 0.3 m, some roots reach depths of 1.0 to 1.4 m, while lateral root extension is up to 1.0 m (Iwama, 2008; Johansen et al., 2015; Zarzyńska et al., 2017).
Sweet cherry trees have a heart-rooting system where roots reached depths of 1 m, sometime up to 2 m. Sweet cherry has the greatest expansion of lateral root at a radius of 1 m around the tree trunk (Balandier et al., 2007). Willows in SRC have a rooting depth of 0.3 to 0.4 m, at good rootable sites down to 1.0 m (Paulson et al., 2003; Dimitriou et al., 2009). Roots can also be found at a depth of up to 1.30 m. On well-watered soils most of the roots are in the upper soil layer (Coppice Resources LTD (CRL), 2006; Dimitriou and Rutz, 2015; Forest Research, n.d.) Most lateral root extension under willow SRC was found up to 1.0 m (Plante et al., 2014; Douglas et al., 2016). These dimensions suggest that in zones where the roots of trees and crops overlap, there will be competitive situations.

There are not many experiments that deal with silage maize in AFS. Most maize trials in AFS study grain maize in arid and semi-arid regions. In these regions' maize is usually irrigated. This makes sense for grain production. However, the irrigation of maize for silage use is questionable in economic terms. Therefore, conclusions can only be drawn from a few grain maize trials.
Studies on water competition in a Kenyan experiment with maize intercropped beneath rows of *Grevillea robusta* (A. Cunn. Ex R. Br.) and *Gliricidia sepium* ((Jacq.) Kunth ex Walp.) showed, that above-ground biomass of maize at milk stage was lower in distances up to 8 m from the tree trunk. In the same distances the volumetric soil moisture content was lower at 1.3 m depth, compared to maize sole cropping. Maize grain yield was significantly reduced within 3 m to tree trunk. A significant reduction of water in soil profiles near to the tree trunk compared to the edges of the tree roots was observed (Odhiambo et al., 2001). This was confirmed by root distribution. Maize, and the observed trees, had most of their roots in a lateral extension of 1.5 m and in a depth of 0.5 m. A study on water competition of black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) on maize in the Midwest USA stated that "[…] competition for water rather than competition for light seems to be critical in defining the productivity and sustainability of this alley cropping system." (Jose et al., 2000a). If maize is planted with a barrier against tree root growth in maize root zone, and with no barrier as control, the water uptake by maize plants in plot without a barrier is smaller. Water uptake of trees was higher in the plots without barrier. This indicates that the additionally tree water requirement is covered from maize soil water pools. The maize leaf area was reduced under no barrier treatment. As plant height and LAI are the two parameters which determine final biomass of silage maize, a reduction in yield would be expected (Gao et al., 2013). Jose et al. (2000a) has compiled studies which show, that leaf elongation is one of the main plant growth parameters affected by water stress. There are also large reductions in plant height and LAI. This has also been observed in a Turkish irrigation experiment on maize. With decreasing water amount the plant height, leaf mass and the fresh matter yield decreased significantly (Kiziloglu et al., 2009). Gheysari et al. (2009) showed that there is a high significant influence of water supply on total biomass ($p < .0001$). If maize can satisfy its water supply, total biomass can increase about almost half (Gheysari et al., 2009). Literature showed that grain yield of maize stands near hedgerows of *Senna spectabilis* ((DC.) Irwin & Barneby) decreased about 65 % to 95 % compared to maize in monocrop stands (McIntyre et al., 1997).
Crude protein of silage maize in an irrigation experiment showed a reduced content with increased amount of irrigation, dry substance showed an increase (Islam et al., 2012). They

attributed the lower crude protein contents to the transfer from vegetative plant parts into cobs under a balanced irrigation management. Under low irrigation the nutrients (e.g. nitrogen) are accumulated in leaves and not translocated to the cobs, which is observed by the higher crude protein contents under low irrigation management. The nutrients are higher concentrated in fewer biomass.
This indicates that in an AFS with a water competition between trees and crops, the total biomass and crude protein of silage maize will be lower and the dry substance will be higher.

Potato is a drought-sensitive crop, especially at the stages of tuber initiation and bulking (Puértolas et al., 2014). Irrigation experiments in Sweden showed, that there was an influence of irrigation by increasing tuber yield with a higher amount of irrigation, but no influence on starch content in tubers (Ekelöf et al., 2015). However, as discussed in **Chapter III** the performance of crops is cultivar-dependent. Researchers observed that tuber yield will be reduced when water is limited, especially in the above-mentioned phases. A deficit in water supply increased the starch content of tubers (Ayas and Korukçu, 2010). This was also observed in an Uzbek experiment (Carli et al., 2014). The variation in starch content was cultivar-dependent. A study of Oparka et al. (1990) ascribed it to the turgor, which regulated the starch synthesis. If water is limited, the cell turgor is lowered, which results in an increased sucrose-uptake-rate and therefore a higher turnover of sucrose in starch (Oparka et al., 1990). If there is a competition in AFS between trees and potatoes for water, the tuber yield will decrease in the areas near the tree trunk and the starch content will increase.

The woody species in AFS should be chosen according to the root system of the annual crop (Schoeneberger et al., 2012). A greater use of water can be achieved when the planted species differ in root architecture (McIntyre et al., 1997). Singh et al. (1989) already stated that hedge-row intercropping is not recommendable, if trees and annual crops use the same pools of soil water.
The root architecture of the used plants in **Chapter II** and **III** (cherry tree, willow SRC, silage maize and potato) did not differ strongly from each other, wherefore competition for water in the observed systems might occur. As a consequence, if deep-rooted trees are planted, agricultural crops with a deeper rooting system should be chosen in the first few years. These crops reach deeper ground water pools, while the tree roots are shallow. In later years, when the trees will root deeper and cover their water supply from deeper layers, crops with a shallower rooting system can be chosen. However, this is partly contrary to the idea of combining tree species and crop species for light use. While in early years the shade of trees is still relatively small, shade-intolerant crops such as maize can be grown. In later years when shade increases, shade-tolerant crops should be used.
By mouldboard ploughing near the tree trunk the root competition can be tempered. The horizontally extending roots in the upper soil layer are cut off and tree roots are oriented in deeper soil layers below the tree strip. As a result, no roots in plough depth should grow and the arable crops can spread their roots (Bender et al., 2009; Kaeser et al., 2010). This lateral root-pruning is also recommended by other authors so that the competition is decreased (Ong et al., 2002).

6.4.2 Nutrients

It is difficult to distinguish between the influence of water and nutrients in an AFS, as nutrient uptake is realized via the transpiration stream of water.
Concerning nutrient level, this section will only focus on nitrogen as the major component of proteins, nucleic acids, cell wall components, hormones and vitamins and so the central element in plant production (Novoa and Loomis, 1981; Krapp, 2015).
An experiment with maize in Kenya between rows of *Grevillea robusta* (A. Cunn. Ex R. Br.) as a low nitrogen up taking tree showed, that after grain maize harvest the soil nitrate contents in the rootable layer down to a depth of 1 m were 3 to 12 kg ha^{-1} at a distance of 3 m from the tree trunk. Near *Senna spectabilis* (DC.) hedgerows, a high nitrogen up taking tree, the contents were 3 kg ha^{-1} or lower (Livesley et al., 2002). Maize biomass was significantly higher in a greater distance from the trunk of 4.50 – 5.25 m compared to 0.75 – 1.50 m. The authors ascribed this to the fact, that maize near Senna hedgerows shifts its biomass growth more to roots than to above-ground biomass. The higher root mass should secure a better nitrogen uptake in this competitive situation.
An US experiment on walnut-maize AFS with root barriers showed that grain yield was reduced in the treatments with no root barrier (Jose et al., 2000b). They stated, that water is the main competitor. They could also prove nitrogen as an influencing factor. This was proven by lower levels of nitrogen found in the tree leaves of the root barrier treatment, than in the no-barrier treatment. In the barrier plots maize nitrogen uptake was lower from fertilizer, than uptake from soil nitrogen compared to the no-barrier plots. In plots where no competition between roots of trees and maize existed, the maize plants did not have to fulfill their nitrogen requirement from fertilizer, enough nitrogen was available in the soil.
Nitrogen fertilization studies of Cox et al. (1993) showed that nitrogen had an influence on photosynthetic efficiency of leaves. If maize plants suffer a lack nitrogen, the dry matter accumulation is reduced by a decreased LA and also decreased photosynthetic efficiency of leaves. An important phase for dry matter accumulation is between developing the 12^{th} and 18^{th} leaf, a lack of nitrogen will reduce final dry matter yields (Karlen et al., 1987). When less nitrogen is available during the grain-filling period, nitrogen from leaves is translocated to the grain, while leaf senescence is promoted as is photosynthetic efficiency.

Beside the fact that potato has a high water requirement, it also has a high nutrient demand (Tein et al., 2014). Potato yields can be increased with increasing nitrogen supply, up to 280 kg ha^{-1}. A nitrogen fertilizer and irrigation experiment showed that under water deficit, nitrogen will not be the limiting factor, because potato is more affected by water, than by nitrogen to produce maximum yields. This is also ascribed to the lowered nitrogen use efficiency under water stress and the reduced nitrogen transport to plant roots in drier soils (Badr et al., 2012). Nitrogen fertilization can yield up to 33 % more tubers, compared to non-fertilized plots and also increase the amount of marketable tuber fraction up to 16 % (Gao et al., 2015). A high nitrogen supply causes low starch contents in tubers (Bártová et al., 2012). Thus, if not enough nitrogen is available due to the competition by tree roots, the tuber formation will be inhibited and smaller tubers will be formed. Drought and early senescence cause lower starch contents. A pot experiment with different nitrogen availabilities showed that with increasing nitrogen supply the nitrate content in tubers increased and the starch content decreased (Putz, 1989; Lin et al., 2004).

It was shown that the supply of light, water and nutrients changed by alley cropping with trees. Each of these three factors has a significant impact on growth of the understory crop in its own way. If competition with woody species causes a deficiency in the agricultural crop, this leads to less growth and, as a result, to lower yields and changed qualities. A reduction in light can affect soil temperature and the release of nutrient from organic and inorganic sources (Baligar et al., 2001).
Kiziloglu et al. (2009) stated that water (and so on nutrients) is the main limiting factor in yield production in semiarid regions. Linked to the findings in **Chapter III** water and nutrients will be the major limitation in southern Europe, while in central and northern Europe it will be the availability of light.
Jose et al. (2000a) stated “Further, with annual pruning and periodic thinning to create high-value timber, light may never become a significant limiting factor in this system.”.

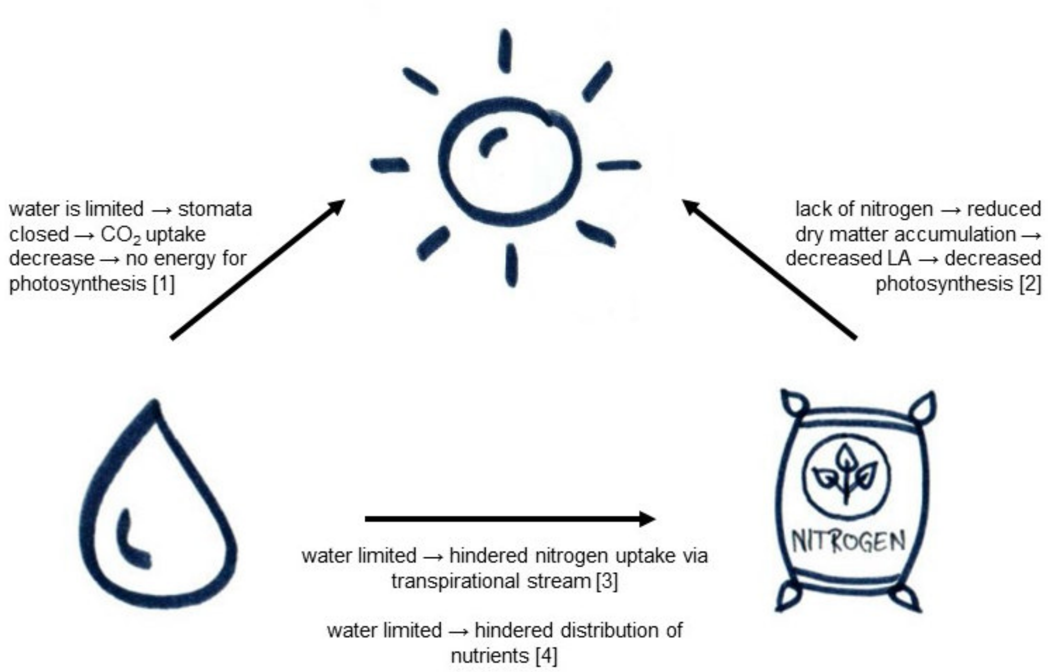


Figure 3: Relationship between the three main plant growth influencing factors light, water and nutrients (e.g. nitrogen) (own figure, based on [1] Tezara et al. (1999), [2] Cox et al. (1993), [3] Islam et al. (2012), [4] Jose et al. (2000b)).

6.5 Economic performance

In this section the economic performance of strip-wise planted trees for SRC and tree strips for high-valuable timber usage will be discussed.

The first aspect, which has to be taken into account when farmers want to establish an AFS is, that the area required by the trees will be lost for agricultural crop production over a long period of time. However, an additional income from the revenue of the wood is expected, which is only produced in the harvest years and not every year.

For economic calculation it was assumed, that wood can be harvested for valuable-timber production after a lifetime of 60 years, whereas SRC strips are harvested every third to fifth year, for a period of 21 years. For simplicity, it was assumed that all the high-valuable timber trees are harvested at once, after 60 years. Under field conditions, only a certain number of trees would be harvested each year after reaching valuable-timber quality and at the same time new trees would be planted. However, it is difficult to calculate the time when the individual trees have reached their timber maturity. This depends on many factors (including pruning and secondary diameter growth).

Table 4 and **Table 5** calculate the annual profit of a theoretical, one hectare-sized AFS with three tree strips for valuable-timber wood production or SRC production with silage maize and potatoes, in comparison to a monoculture. Therefore, first the contribution margins for silage maize and for potatoes were calculated in the first place. As monocropping yield the observed yields under 0 % shade from **Chapter II** and **III** were used. The trading unit at market for silage maize is the dry matter base and for potatoes the fresh matter base. The services and cost of monocropping silage maize and potato were taken from the online calculation tool for cash and fodder crops of the LEL (LEL, 2018a, 2018b). It was assumed that an agricultural contractor was hired for chipping of silage maize, and the harvest of potatoes was carried out by a potato harvester with bunker. The results can be found in **Table 2**. It could be shown that a sole silage maize stand gains a contribution margin of 801.38 € ha^{-1} yr^{-1}, while a sole potato stand would gain 7555.21 € ha^{-1} yr^{-1}.

Table 2: Services and costs for crop production of maize on dry matter base and for potatoes on fresh matter base and the resulting contribution margin of crops per year.

			Maize (dry matter base)	Potato (fresh matter base)
Crop Production	**Services**			
	Monocropping Yield	Mg ha^{-1}	21.05	56.85
	Repossession of Biogas Plant Residues	€ ha^{-1}	636.00	-
	Price (incl. German value added tax)	€ Mg^{-1}	77.50	199.30
	Total Services	€ ha^{-1}	2267.38	11330.21
	Costs			
	Seeds	€ ha^{-1}	170.00	1685.00
	Plant Protection	€ ha^{-1}	75.00	385.00
	Fertilizer	€ ha^{-1}	738.00	631.00
	Variable Machine Cost	€ ha^{-1}	130.00	360.00
	Agricultural Contracting Business Machines	€ ha^{-1}	353.00	714.00
	Other variable Costs	€ ha^{-1}	-	-
	Total Costs	€ ha^{-1}	1466.00	3775.00
	Contribution Margin Crop per Year	**€ ha^{-1} yr^{-1}**	**801.38**	**7555.21**

The establishment of an AFS, either for high-valuable timber or an SRC for energy production, causes planting costs. The cost for establishing and services (including prices for valuable-timber wood and by-products) of a high-valuable timber AFS were taken from Morhart et al. (2016). The calculation was based on 30 trees per hectare, a high-valuable wood yield of 1.4 m³ sub per tree and a price of 400 € per m³ sub, which resulted in 16.800 € ha^{-1} for high-valuable timber as main product. Bark, branches and twigs can be sold as firewood, at 132 € per tree. Planting material for one tree was set to 5 € and the tree guard material was 3.5 € per tree. In the first years the trees have to be pruned, to reach timber quality. This has to be done in year 3, 6, 8 and 10, with increasing costs of 2.5, 5, and in year 8 and 10, 7.50 € per tree with increasing tree height. Additionally, the tree strip has to be mulched every year over 60 years, which costs 0.005 € m^{-2}. All three tree strips have in total 1305 m². This work can be done in one hour, with an assumed man-hour cost of 30 €. Harvest is done motor-manual by chainsaw. Per tree costs of 102 € are incurred. This makes an annual payment for wood of 240.26 €. Average yields of 30 t DM ha^{-1} were assumed for willow SRC, in a three-year rotation (Unseld et al., 2014). For the tree strips with 1305 m² a yield of 3.92 Mg DM occurs. Actual wood chips prices for southern Germany were calculated with 93.73 € t^{-1} at a water content of 35 % (C.A.R.M.E.N. e.V. - Hackschnitzel, 2019). On dry matter base this corresponds to 144.20 € t^{-1} DM, which is in total 73.67 € for the assumed system. Assumptions for establishing, price per cutting, planting cost, mortality rate and harvest cost of SRC were taken from the online tool for SRC calculation of the LEL (2010). For three tree strips with two double-row each, 1164 cuttings were needed, with 0.12 € cutting^{-1} and planting costs of 0.09 € cutting^{-1}. Harvest is done by chainsaw and mobile chopper. This is the only profitable method for areas less than or equal to 1 ha (Unseld et al., 2014). So, 2700 € ha^{-1} were assumed. The area of SRC strips is 1305 m² and harvest has to be done every third year, over a time of 21 years. The recultivation costs of 1000 € ha^{-1} for an SRC were transferred to a timber AFS because the same machinery is needed. For timber AFS this adds up to an annual payment of 240.26 € ha^{-1}, while for Energy SRC it would result in -10.29 € ha^{-1} (**Table 3**). This negative value is caused due to the fact, that SRC with an area smaller than 1 ha are not profitable.

Table 3: Services and costs for wood production of trees in a high-valuable timber AFS and for willows grown in an SRC for energy purpose and the resulting contribution margin for the wood per year.

			Timber AFS	Energy SRC
Wood Production	**Services**			
	Yield (Timber m³ sub ha^{-1}; SRC Mg DM ha^{-1})		42.00	3.92
	Price (main product)	€ ha^{-1}	16800.00	73.67
	Price (by-product; firewood)	€ ha^{-1}	3960.00	-
	Total Discounted Services	€ ha^{-1}	20760.00	2671.81
	Costs			
	Site preparation (1st year)	€ ha^{-1}	9.79	9.79
	Planting material (1st year)	€ ha^{-1}	150.00	244.44
	Tree Guards (1st year)	€ ha^{-1}	105.00	-
	Replacement of dead trees (1st year; +15% of planting material)	€ ha^{-1}	22.50	36.67
	Cultivation (pruning in 3rd, 6th, 8th and 10th year)	€ ha^{-1}	675.00	-
	Mulching of tree strip (over 60 years)	€ ha^{-1}	2191.50	-
	Harvest (Timber in 60th year, SRC every 3rd year for 21 year)	€ ha^{-1}	3060.00	2466.45
	Recultivation (Timber in 60th year, SRC in 21th year)	€ ha^{-1}	130.50	130.50
	Total Costs	€ ha^{-1}	6344.29	2887.84
	Annual Payment Wood	**€ ha^{-1} yr^{-1}**	**240.26**	**-10.29**

Until now, only the reduction of the cropping area by the tree strips were taken into the calculations. But as seen in **Chapter II** and **III**, shade also reduced the crop yields. To calculate the shade-induced reduction the assumptions for calculation for AFS with timber trees and AFS with SRC-strips are listed in the Appendix, **Table A 1**. The calculation is based on a one hectare-sized field, with 145 m length and 69 m width. Three rows of trees were established with a width of 3 m.

For timber AFS the different shade levels (12 %, 26 % and 50 %) used in **Chapter II** and **III** were assumed as static, semi-circle around the tree trunks, but only in the northern direction, because the tree-strips had an optimal orientation from east-to-west. This orientation ensures that most of the shade casts in the tree strip itself (Bender et al., 2009).

In a timber AFS during the first 25 years, no shade competition will be expected due to the small tree height, the dense crowns, which do not touch each other, and do not cast much shade on the field. Therefore, only the lost area by the tree strips causes yield reductions. From year 26 for the remaining 35 years, the previously determined shade-induced yield reductions are expected (**Table 4**). The reduction of the plant production costs for maize and potato are listed in **Table 2**, considering only the area of the tree strips. For silage maize this makes an aggregated contribution margin of 864.16 € ha^{-1} yr^{-1}, which is 8 % higher than in monocropping. The profits made by the wood after 60 years are able to compensate financial losses through AFS. However, for potatoes with a total of 6149.81 € ha^{-1} yr^{-1}, the profit is reduced about 19 %. The results in **Chapter III** have shown that potatoes are able to achieve high yields, up to a shading of 26 %. But according to the high price achieved for potatoes, and the high harvest volumes, a reduction of tree strips during the first 25 years would result in financial losses. In the remaining 35 years these reductions are increased by the losses caused by shade.

Table 4: Aggregated contribution margin of a timber AFS per hectare and year for silage maize and potato intercropping.

			Silage Maize	Potato
Timber AFS	Contribution Margin Crop Production (1st - 25th year)	€ ha^{-1} yr^{-1}	696.80	6569.25
	Contribution Margin Crop Production (26th - 60th year)	€ ha^{-1} yr^{-1}	571.83	5438.34
	Total Discounted Services Wood Production	€ ha^{-1}	20760.00	20760.00
	Total Costs Wood Production	€ ha^{-1}	6344.29	6344.29
	Contribution Margin Wood Production	€ ha^{-1}	14415.71	14415.71
	Contribution Margin Wood Production per year	€ ha^{-1} yr^{-1}	240.26	240.26
	Aggregated Contribution Margin Timber AFS	**€ ha^{-1} yr^{-1}**	**864.16**	**6149.81**

There are no values on light reduction and shading of willow SRC. Therefore, the values which were determined for the valuable-timber trees were used. Since a 6 m high cherry tree was measured, these values were transferred to a willow SRC. A willow SRC will reach a height of approximately 4 m within a three-year harvest cycle (see **Chapter I**). Since an SRC forms a dense, hedge-like stock, continuous shading strips were assumed instead of semi-circles (**Table A 1**). For the first year of the rotation it was expected that the full yield reduction would not occur, as the SRC first has to achieve a height, which influences crop growth. Thus, in the first year 33 % of the yield reduction was assumed, in the second year 66 % and in the third year the full reduction (**Table 5**).

For silage maize an aggregated contribution margin of 721.44 € ha^{-1} yr^{-1} will be achieved, while for potato 6888.27 € ha^{-1} yr^{-1} could be gained, which corresponds to a reduction of 10 % and 9 %, respectively. The reason why the SRC-AFS reaches such small values can be attributed to the small area, where wood is cultivated in this system. Also, the yield reduction of arable crops is greater than in Timber-AFS. This is due to the fact, that the shade zones in an SRC-AFS are larger, as shown in **Table A 1**. Although, there are no additional costs of care taking in an SRC, as seen for high-valuable timber trees, by pruning and mulching. The three-year harvest generates more costs. In addition, the profits for wood are lower, than for valuable-timber wood. The timber trees generate a capital of 20760.00 € ha^{-1} during their lifetime. The 73.67 € ha^{-1} for SRC wood chips accumulated with 3.5 % over the 7 harvests generated 381.69 € ha^{-1} at each harvest.

Table 5: Aggregated contribution margin of an energy SRC per hectare and year for silage maize and potato intercropping.

			Silage Maize	Potato
Energy SRC	Contribution Margin Crop Production (1st year)	€ ha^{-1} yr^{-1}	766.55	7226.88
	Contribution Margin Crop Production (2nd year)	€ ha^{-1} yr^{-1}	731.73	6898.56
	Contribution Margin Crop Production (3rd year)	€ ha^{-1} yr^{-1}	696.90	6570.24
	Total Discounted Services Wood Production	€ ha^{-1}	2671.81	2671.81
	Total Costs Wood Production	€ ha^{-1}	2887.84	2887.84
	Contribution Margin Wood Production	€ ha^{-1}	-216.03	-216.03
	Contribution Margin Wood Production per year	€ ha^{-1} yr^{-1}	-10.29	-10.29
	Aggregated Contribution Margin Energy SRC	**€ ha^{-1} yr^{-1}**	**721.44**	**6888.27**

So, finally, from an economical point, timber AFS is profitable for silage maize, but not for potatoes. The cultivation of SRC strips on one hectare is not worthwhile, neither for silage maize, nor for potatoes. To make this system profitable, more land is needed. However, these values are not able to represent the reality perfectly, as this calculation is based on the fact that the same crop is cultivated in every year. In fact, these profits would change based on the implemented crop rotation and, thus, annually changing crops. Additionally, a financial support by the common agricultural policy of the EU could be provide an incentive for this system. By promoting the ecological impact of tree strips, financial deficits could be compensated.

6.6 Environmental performance

In the previous chapter, a financial reward was proposed for ecological services in the form of tree strips in the agricultural structure. After Jose (2009), the four main factors for ecosystem services and environmental benefits by AFS are (1) carbon sequestration, (2) biodiversity conservation, (3) soil enrichment and (4) air and water quality. Additionally, for carbon sequestration, Palma et al. (2007) listed erosion control, reduced nitrogen leaching and improved landscape biodiversity as benefits.

AFS can contribute to carbon storage, due to the conservation of soil in the tree rows and the carbon sink function by trees. Studies of Montagnini and Nair (2004) found that agroforestry in temperate regions is capable of storing carbon in the amount of 63 Mg ha^{-1} yr^{-1}. The same study also showed, that the potential carbon sequestration of AFS in the United States by 2025 is estimated to 0.92 Mg ha^{-1} yr^{-1} in alley cropping systems, and 0.83 Mg ha^{-1} $year^{-1}$ in a short rotation woody crop plantation. Alley cropping for timber has a longer cutting cycle and so the carbon is stored for a longer time period than in SRC, with its shorter cutting cycle. The carbon storage of 0.83 Mg ha^{-1} yr^{-1} is related to a SRC plantation on hectare size. The assumed system in **Chapter 6.5** with strip-wise cultivated rows of SRC would have a lower storage. Only 13 % of one hectare would be covered with SRC. On the basis of this, a theoretical carbon storage of 11 Mg ha^{-1} yr^{-1} occurred. Most of the carbon is stored below ground. The storage potential of a timber AFS is difficult to calculate due to the different age structures of the individual trees (due to tree replacement after single tree harvest) and due to different tree species.

The biodiversity conservation can occur in different ways in an AFS. According to Jose (2009), it provides habitats, preserves germplasm of sensitive species, reduces the conversion of natural habitat, creates corridors in open agricultural sites and helps to preserve the biological diversity (Jose, 2009). Tsonkova et al. (2012) investigated the ecosystems services of alley cropping of SRC on agricultural sites. They reviewed literature and showed that the diversity of plants in SRC strips depends on the size of the plantation, the surrounding landscape and the previous land use, and the used species of SRC. They also showed that woody strips serve as a winter habitat for diverse ground beetles. A walnut alley cropping system in the temperate regions of Missouri, USA, showed more arthropods in total, than in plots without vegetation between the trees (Stamps et al., 2002). A higher population of earthworms was found near tree strips than in monocrop stands in an AFS in Canada (Thevathasan and Gordon, 2004). This was attributed to the litter contribution. A higher population of birds was found in willow SRC in Sweden. More species which nest in shrubs or on the ground were found in willow SRC, than in monocrop farmland (Berg, 2002). In addition, the wood structures of SRC or timber AFS provide a permanent structure for breeding birds. Since harvesting of SRC takes place only every third to fifth year in winter, the birds are offered a permanent habitat.

Soil enrichment, the improvement of the soil's chemical, physical and biological properties, is also listed as an ecological benefit of AFS. The above-mentioned higher density of earthworms can contribute to a beneficial soil structure and stability (decreased soil bulk density, increased decomposition of soil organic matter, improved soil stability) (Thevathasan and Gordon, 2004). An experiment in Missouri with tree strips of *Quercus palustris* (Münchh.), *Quercus bicolor* (Willd.) and *Quercus macrocarpa* (Michx.) showed a higher total number of pores than in row crops of soybean or maize. These findings were ascribed to a higher root decay and soil fauna activity (Seobi et al., 2005). Also, a lower bulk density was found in the AFS strips, compared with the crop site. The higher number of pores, and the loose, soil can reduce erosion, due to a higher infiltration. The higher saturated hydraulic conductivity additionally supports this fact. The kinetic energy of raindrops is lowered by the (ground) vegetation of the woody strips and also the vegetation slows down the flow velocity of the water, whereas the soil has more time for infiltration. This process also reduces the erosion and so on the loss off sediments and nutrients by surface runoff. The microbial biomass carbon in a 47-year old pecan-cotton (*Gossypium hirsutum* L.) and *Carya illinoinensis* (Wangenh.) K.Koch) AFS was more than double of cotton monocropping (375 mg kg^{-1} vs. 163 mg kg^{-1}). While in a 3-year old pecan-cotton AFS the microbial biomass was not significantly different from monocropping cotton (118 mg kg^{-1}) (Lee and Jose, 2003). The organic matter of the old pecan-cotton AFS was 3.4 %, while the younger AFS had 1.5 % and the cotton monocropping 2.1 % These results showed, that there is an initial phase, before these positive impacts of these systems occurs.

The improvement of water and air quality is also one of the listed advantages of AFS. There is the so called 'safety net' hypothesis for water quality in an AFS (Jose et al., 2004). This means, that the tree roots capture nitrate and other nutrients that are leached in deeper soil layers and prevent the accumulation of these nutrients in the soil water bodies. Trials have shown that a sole crop of maize has more nitrate available for leaching, than in stands near a tree or hedgerow (Livesley et al., 2002). The mentioned AFS of cotton and pecan trees showed at a depth of 0.9 m a nearly 30 % reduction in nitrate concentration compared to the concentration in 0.3 m depth (Allen et al., 2004). In years with high precipitation and higher runoff events in

AFS there was significantly lower runoff than under sole-cropping. The trees improve infiltration and water holding capacity of soils. Also, the sediment losses were reduced in AFS (Udawatta et al., 2010).

Often the soil and water quality are highlighted in context with AFS, as seen above. But also, the air quality could be influenced by AFS. The trees could influence the concentration of greenhouse gases in atmosphere. Studies found, that trees are able to mitigate the N_2O and CO_2 emissions from soils, and be a sink for CH_4 (Mutuo et al., 2005). The CO_2 emissions are controlled by the above-mentioned carbon storage. N_2O is reduced by reduction of nitrogen fertilizer and soil tillage in tree rows. Also, tree roots can uptake nitrate up to a certain distance from tree trunk, which is not available for crops. Thus, this nitrate cannot be reduced to N_2O. AFS soils are also able to compensate CH_4 emissions. Due to the non-tilled soil beneath the trees, soil microorganisms stay intact. There are some methanotroph bacteria in soil which use CH_4 as a carbon source and, therefore the soil under trees is a higher CH_4 sink, than agricultural soil (Malghani et al., 2016). On the other hand, it also has to be taken into account that trees are a higher source for volatile organic compounds (VOCs) than arable crops, especially for isoprene. The solar irradiance can degrade some of the VOCs to chemical compounds that promotes ozone production and aerosol formation (Pio et al., 2005). This has a negative impact on air quality. A 6.5 ha sized willow short rotation coppice peaked in values for isoprene around 20 µg g_{dw}^{-1} h^{-1}, which is much higher than the values for arable crop, which range between 0 - 0.5 µg g_{dw}^{-1} h^{-1}, depending on the crops (Copeland et al., 2012). This effect, however, is considerably higher in the case of the extensive cultivation of trees, than in the case of strip-wise cultivation in AFS between arable crops.

In general, (strip-wise) AFS are able to make a greater contribution to the environment than monocropping.

6.7 Further research

The results showed that AFS are complex systems of land management. There is not only one main factor of influence, but a multitude of factors interact. Due to the manifold forms of AFS, there are numerous other research approaches. Starting with the possible combinations of perennial and annual cultures, the tree species, the understory crops, the distance and densities of the plant stand and site characteristics.

While doing the research on **Chapter II** and **III**, often the point of criticism came up, that in a real AFS the tree shade does not remain static on the surface. It migrates over the crop area during the course of the day and the year. Rosskopf et al. (2017) showed a good visualization on how tree shade is changing in the course of year. The shade is not, as in **Chapter II** and **III**, rectangular on the agricultural crop, it is an ellipse on a parabolic course. An experiment was done with artificial, uniform net shade and artificial, spotted shade by slats on durum wheat (*Triticum turgidum* L. subsp. *durum*) in comparison to an AFS with walnut (*Juglans regia* L.) (Dufour et al., 2013). Although spotted shade by slats copy the light spectrum of an AFS with trees better than nets, there were no yield differences observable between these two artificial shade treatments, but they differed significantly from walnut AFS. A trial in New Zealand compared alfalfa (*Medicago sativa* L.) under net shade and slats shade with alfalfa-pine stands (*Pinus* sp. L.) (Varella et al., 2011). It was observed, that the slat shade reproduces the tree shade and the light spectrum (red:far-red ratio; R:FR) better, than shade nets. Tree (or other, higher plants) canopy decreases the R:FR ratio of the light reaching the understory crop (Franklin and Whitelam, 2005). In shade the part of far-red light is increased by reflection from cell walls of the trees and the part of red light is decreased by absorption by tree chlorophyll (Li et al., 2012). It should be investigated, how the plants grow, when the light spectrum caused by artificial shade corresponds to that of shade by trees.

Literature has shown that AFS in the tropics and subtropics are already a well-researched system. These systems are also available in different ages (chronosequence), which makes research much easier. In the temperate zone, AFS of different ages are missing, especially with regard to high-valuable timber usage. Younger trees, with a smaller crown volume, cast less shade than older ones. There are also tree species with a bright crown and a dense crown. These facts have not yet been adequately addressed in research. It is therefore advisable to observe different tree species at different age levels and the level of shade they create. Then, with these values (also by artificially created shade), agricultural crops and genotypes can be determined, which are shade tolerant. Additionally, the shade influence of an SRC in different growth years is not quite well documented in literature.

As seen in **Chapter II** and **III** there are crops that are more shade-tolerant than others, but at a certain point a decrease in yield was observed. Another approach is to test how renewable resources (= for non-edible purpose), like medicinal, aromatic, dyeing or spice plants act under shade. Many of these plants naturally grow in the (partial) shade of forests. Thus, they are shade-tolerant. Currently, they are also subject to wild collections, which are not always sustainable, and there is a strong fluctuation in the quality of wild collections. Several medicinal species which are subjected to wild collections are endangered species. One possible approach to reduce the negative effects of wild collections and use the shade-tolerance, could be the cultivation in silvoarable AFS (Rao et al., 2004). A trial on lemon balm (*Melissa officinalis* L.) has shown that under a 50 % blue net shade the biomass yield was not influenced. However, a non-significant increase in oil content was observed when plants were grown under these nets. Even if there is a reduction in yield in these crops, consistent or even higher profits can be achieved through increased quality. Ginseng (*Panax ginseng* C.A. Meyer) is known as a plant that needs shade. If the solar irradiance is too high, photosynthesis is inhibited which can end in permanent leaf death (Li, 1995; Parmenter and Littlejohn, 2000). At 55 % shade sage (*Salvia officinalis* L.) had the highest oil concentration (Li et al., 1995). Carotenoids showed a 75 % increment at 75 % shade (Zervoudakis et al., 2012). Thus, the production of these renewable resources could be a possibility in AFS. In the first years, when trees and shade are small, agricultural crops could be established. In later years when trees (crowns) are larger, plants for non-edible purposes could be an option (if mechanization, infrastructure and market structures are available). The cultivation in AFS would create a shady climate, but at the same time it allows mechanization and controlled cultivation. Fungal diseases could, however, pose a problem. Nearly no plant protection agents are allowed in medicinal, aromatic, dyeing or spice plants. But these plants are very susceptible to fungal diseases. Shade increases the duration of leaf wetness. This was shown in a wheat experiment in Australia, where the risk for powdery mildew was higher. Moisture from rain or dew stays longer in the plant stand, if its shaded (Sudmeyer and Speijers, 2007). There are already some research approaches in this direction. Suitable plants can be screened, their performance and quality under shade should be estimated, as well as the optimization of the agricultural crop procedures.

7 Summary

The cultivation of several plant species on the same area of land, at the same time, is called Agroforestry (AFS). In the less developed countries and the countries of the tropics and subtropics, AFS are the main form of land management. Reasons can be found in the low degree of mechanization and the low costs of labor. AFS used to be widespread in the industrial nations, too. Over the years, however, these traditional forms have been converted into highly efficient agricultural sites. Agricultural and forest production has been separated spatially. In Germany, this was mainly due to land consolidation, which resulted in large, uniform and easy-to-farm fields. In recent years, however, this situation has been reconsidered. The positive environmental benefits and the aspect of biodiversity protection of agroforestry systems have been recognized. There are numerous ecological, economic and social aspects, which make agroforestry attractive again. However, a competitive situation always arises when plants are cultivated together. In addition, there are multiple forms of AFS. Special attention has to be paid to the planting of the woody, perennial component, as it remains on the field for several years.

Against this background, this thesis deals with the possibilities of establishing the wood component in an AFS as a short rotation strip. Combinations of different tillage and weed management practices on willow growth and yield were tested. Furthermore, the influence of shade, which is listed as one of the three main influencing factors in AFS, is discussed. Agricultural crops behave differently, on shade casts by the woody component on the understory crop, depending on their need for light. To test this, maize was used as a shade-intolerant C4 plant, which reaches its light saturation close to maximum solar irradiance. In contrast, potato was tested as a more shade-tolerant C3 plant. Observations on growth, yield and quality should provide information on their suitability for cultivation under shady conditions in AFS.

Various hypotheses were developed and examined for the purpose of testing. In the following, the most central research results will be briefly outlined.

1. There are no other recommendations for the establishment of a willow short-rotation coppice except ploughing in autumn, harrowing in spring and broad herbicide application. In the current discourse on biodiversity improvement and climate change, forms of reduced tillage (chisel plough + ley crop, no-till) with adapted herbicide-saving weed control can ensure successful SRC growth and, as a result, high yields while saving pesticides and fossil energy.

An adequate combination of soil tillage and weed management showed to be important for high yields, whereas the necessary weed management depends on the used soil tillage. The conventional establishing method of ploughing, harrowing and a broad herbicide application, had the highest yields in comparison to the other measurements. Covering with wood chip mulch cannot be recommended for any of the tillage systems, due to the strong competition. In the chisel plough treatment, the ley crop is also a major competitor, only broadcast applied herbicides can reach comparable yields. Under no-till all treatments, except of mulching between willow rows, can achieve good yields. The mechanical weed control of rotivation between willow rows can also be used in mouldboard plough or no-till. For ecological and erosion-protection reasons, no-till treatments may be of interest.

2. Maize, as a plant with a high light saturation point, is already negatively influenced in its growth, the biomass, biogas and methane yield, as well as the quality determining compounds by low amounts of shade.

While plant heights and leaf area index were already reduced during plant growth, this also reduced the final biomass yield. Depending on the year, these reductions occurred from 26 % or 50 % shade. Shading maize at a level of 50 % almost reduced the final biomass yield about 50 %. Significant reductions in yields could already be observed even from the lowest shade levels of 12 %. On the other hand, crude protein and crude ash increased at 26 % shade, which negatively influenced the yield of biogas and methane. The C4 plant maize cannot be recommended under shade levels higher than 26 %. However, even under the strongest shading, higher biomass yields could be achieved compared to other biomass crops under full sunlight.

3. Potatoes, known as shade-tolerant plants, are able to produce yields and qualities comparable to those of unshaded plants with lower levels of solar irradiance (caused by shading). There will be no differences in their growth.

The height growth of the potatoes was not influenced by shade. The yield determining parameters, such as number of plants per square meter and number of stems per plant, were not changed by shade. A reduction in the number of tubers per plant and tuber mass per plant occurred depending on the year. The same was observed for the yield. In years with high solar irradiance yields were not reduced at all or only from 50 % shade, while in years with low irradiance from 26 % shade reductions occurred. The quality of the tubers was not influenced. Shading potatoes up to levels between 26 % and 50 % will be possible.

For the preservation of biodiversity, alternative, herbicide saving weed management systems are needed. The research on **alternative establishment methods for short-rotation coppice** had shown that some weed management treatments work better in specific tillage systems than others. Mouldboard ploughing as soil tillage works well against grasses and, by the soil turning effect, the weed seed bank is shifted to deeper soil layers, which makes it difficult for weeds to emerge. Under this soil tillage herbicides should be used with a broad mode of action in pre- and post-emergence. This also reduced the risk of resistance formation. Mechanical weed treatment between willow rows could also be an herbicide saving alternative, except of rolling. The ley crop in the chisel plough treatment offers an additional competition factor for weeds and suppressed them. However, the soil tillage systems need a broad application of herbicides, otherwise the competition for the willows is too high. Under no-till only weeds from the upper soil layers germinate and so all weed management systems, except of mulching between willow rows, offer an option.

Expect of the observed crops maize and potato, **other crops** can serve as interesting intercropping partners in AFS. In grain crops, like wheat and rice, shade influences the yield determining parameters (grains per era, ears per m² and 1000-grain weight) negatively. Also, in oil crops, like soybeans and canola, the shade reduced the translocation of assimilates. Leguminous crops showed no change in yield by compensating the reduced beans or seeds by a higher 1000-grain weight. Changes in the quality of fodder species were observed, whereas C4 species were more susceptible than C3 species. This was proven in **Chapter II** and **III**, were maize was more affected by shade than potatoes.

In addition to competition for light, the other two factors are **water and nutrients**. A sufficient supply of water is important because a reduction of this supply leads to a disturbed mass and nutrient transport (in particular nitrogen), which results in decreased leaf area and so in a reduced photosynthetic efficiency. For maize this has been shown by the fact that the biomass is reduced and the crude protein content is increased. Potatoes depend more on water than nitrogen. A low supply of water, especially during tuber initiation and bulking, will led to smaller tubers with a higher starch concentration due to the turgor. Therefore, it is stated that water is the limiting factor in semiarid regions, while light will be the major limiting factor in Northern hemispheres.

While AFS are an important promoter of biodiversity and ecological benefits, the **economy** of such a system is difficult to evaluate, due to the long lifetime, especially in systems used for the production of high-valuable timber. This is due to the increasing influence of the trees on the arable crop over the years, and on the other hand, it is difficult to calculate profits from the sale of valuable timber after several decades. A modelled AFS with strips of willow for short rotation and strips of high-valuable timber trees resulted in a profit of 801.38 € ha^{-1} yr^{-1} for a pure maize stand, while this profit would be increased by 8 % through planting of strips of high-valuable timber and reduced by 10 % for short rotation strips. In the case of potatoes, the achieved net profit would be 7555,21 € ha^{-1} yr^{-1}, while the two different tree usage strips would reduce it by 19 % (high-valuable timber) and 9 % (willow SRC), respectively. The strong reduction in short rotation strips is due to the low economic efficiency of this strip size. For the high-valuable timber strips, it is difficult to calculate, since the profits only accrue after 60 years or more. In SRC, the low prices for wood chips and the high manual work at harvesting are problematic. This, in combination with the reduction resulting from the loss of area cultivated by the tree strips, make this type of wood usage in a one hectare-sized system uneconomical. Potatoes themselves fetch such high prices that even the slightest loss in yield leads to significant reductions in profits.

Ecological advantages which can occur by AFS are the reduced usage of fossil fuels because the strips are no longer tilled and the carbon storage of trees by absorbing CO_2 and storing it in their root mass. The modelled one hectare-sized system with SRC would be able to store a carbon amount of 11 Mg ha^{-1} yr^{-1}. For valuable timber systems it would be much more complex to calculate, due to the many different factors influencing the carbon storage (trees of different age, different tree species). The strips also provide a permanent habitat for soil organisms and birds. A richness in the arthropod fauna occurs, more earthworms were found, which improve the soil structure and also the number of birds increased. In addition, the tree strips improve the soil structure through a lower bulk density and organic deposits, which increase infiltration and reduce the flow velocity of the water, which counteracts erosion. The tree strips also prevent the leaching of nutrients into the groundwater, for nitrate there was a reduction of up to 30 % by trees. By absorbing CO_2, the trees ensure improved air quality, the absence of fertilizers in the tree strips indicates that less nitrogen as N_2O is lost and some soil organisms in the tree strips use CH_4 as a carbon source.

Further research is needed on the influence of other tree species, in different ages, on arable crops. Also, the used methodology for the evaluation of shade can be improved, because shading nets cannot completely replicate the light spectrum in an AFS. The light spectrum underneath trees showed a decrease in the red spectrum and an increase in the far-red spectrum by the chlorophyll absorption of the tree leaves. There has to be a dynamic trial setup to simulate the course of the sun during the day and the year. Another focus should be given to different crops. While in the first years, when tree crowns are still small and, thus, the shade influence is low, conventional agricultural crops can be cultivated, in later years with a greater shade influence the cultivation of medicinal, aromatic, dyeing and spice plants can be interesting. Many of these plants tolerate high levels of shade, due to their forest origin from (partial) shade.

It could be shown that it is possible to make a valuable contribution to biodiversity with AFS. By using adapted combinations of soil tillage and weed management systems, fossil fuels can be saved through reduced tillage. The use of chemical plant protection in the tree strips can be reduced by the sole application within the SRC strips or avoided altogether by mechanical weed control. In high-valuable timber systems there is usually no weed management necessary. Additionally, the trees strips offer a habitat and food basis for small vertebrates and some arthropods (hymenoptera, coleoptera, lepidoptera and diptera). The permanent planting of the strips reduces greenhouse gases and thus counteracts climate change. Therefore, AFS are a valuable form of land management to reduce current environmental problems on a national and global scale.

8 Zusammenfassung

Der gemeinsame Anbau von mehreren Kulturen auf ein und derselben Fläche zur selben Zeit wird als Agroforstsystem (AFS) bezeichnet. In den weniger entwickelten Ländern und Ländern der Tropen und Subtropen sind AFS die hauptsächliche Form der Landbewirtschaftung. Dies geht auf den geringen Mechanisierungsgrad und kostengünstige Arbeitskräfte zurück. In den Industrienationen waren AFS früher ebenfalls weitverbreitet. Allerdings wurden diese traditionellen Formen über die Jahre in hocheffiziente Formen der Landbewirtschaftung überführt. Die landwirtschaftliche und die forstwirtschaftliche Produktion wurden räumlich getrennt. Dies geschah in Deutschland überwiegend durch die Flurbereinigung, bei der große, uniforme und einfach zu bewirtschaftende Schläge entstanden. In den letzten Jahren ist es allerdings zu einem Umdenken gekommen. Der positive Nutzen von AFS für die Umwelt und den Schutz der Biodiversität wurde nachweislich anerkannt. Es gibt zahlreiche ökologische, ökonomische und soziale Aspekte, die Agroforst wieder attraktiv machen. Allerdings entsteht immer eine Konkurrenzsituation, wenn Pflanzen gemeinsam angebaut werden. Zudem gibt es eine mannigfaltige Form an Ausprägungen von AFS. Der Anlage der verholzenden, mehrjährigen Komponente gilt ein besonderes Augenmerk, da diese einmal etabliert, für mehrere Jahre auf der Fläche verbleibt.

Vor diesem Hintergrund beschäftigt sich diese Arbeit mit den Möglichkeiten der Etablierung der Holzkomponente als Kurzumtriebsstreifen in einem AFS. Behandelt werden dafür Kombinationen aus verschiedene Bodenbearbeitungs- und Unkrautmaßnahmen auf Wachstum und Ertrag von Weiden. Des Weiteren wird der Einfluss von Schatten untersucht, der als einer der drei Haupteinflussfaktoren in AFS gelistet wird. Landwirtschaftliche Kulturen reagieren, je nach ihrem Lichtbedarf, unterschiedlich auf Schatten den die verholzende Komponente auf die unterwüchsige Kultur wirft. Um dies zu testen wurde Mais als schattenintolerante C4-Pflanze getestet, die ihre Lichtsättigung nahe der maximalen Einstrahlung erreicht. Dem gegenüber wurde die Kartoffel als eine schattentolerantere C3-Pflanze untersucht. Beobachtungen an Wachstum, Ertrag und der Qualität der Inhaltsstoffe sollen Auskunft über deren Eignung zum Anbau unter den schattigen Bedingungen in AFS geben.

Zur Überprüfung wurden verschiedene Hypothesen aufgestellt und untersucht. Im Folgenden soll kurz auf die zentralsten Forschungsergebnisse eingegangen werden.

1. *Bei der Anlage einer Weiden-Kurzumtriebsplantage gibt es noch keine anderen Empfehlungen außer Pflügen im Herbst, eggen im Frühjahr und eine breitflächige Herbizidapplikation. Im Zuge der derzeitigen Diskussion über die Steigerung der Biodiversität und den Klimawandel, können Formen der reduzierten Bodenbearbeitung (Grubber + Untersaat, Direktsaat) mit angepassten, herbizidsparenden Unkrautkontrollen ein erfolgreiches KUP Wachstum ermöglichen, hohe Erträge erzielen und gleichzeitig Pflanzenschutzmittel und fossile Energie einsparen.*

Eine angepasste Kombination aus Bodenbearbeitung und Unkrautkontrolle zeigte sich als wichtig für hohe Erträge, wobei die nötige Unkrautkontrolle auf die Bodenbearbeitung abgestimmt sein muss. Das herkömmliche Etablierungsverfahren aus pflügen, eggen und einer flächigen Herbizidapplikation brachte im Vergleich zu den anderen Varianten auch weiterhin die höchsten Erträge. Ein Abdecken mit Mulch aus Holzhackschnitzeln kann bei keiner der Bodenbearbeitungen auf Grund der Konkurrenz empfohlen werden. In der Grubber-Variante stellte die Untersaat ebenfalls eine große Konkurrenz dar, lediglich der flächige Einsatz von Herbiziden erreichte hohe Erträge. Wenn keine Bodenbearbeitung erfolgen soll, können alle Unkrautregulierungsmaßnahmen mit Ausnahme des Mulchens zwischen den Weidenreihen gute Erträge erzielen. Die mechanische Unkrautbekämpfung mittels Fräse zwischen den Weidenreihen kann beim Pflügen oder der Direktsaat eingesetzt werden. Aus ökologischen Gründen und zum Erosionsschutz können Direktsaat-Varianten von Interesse sein.

2. *Mais als Pflanze mit einem hohen Lichtsättigungspunkt wird bereits durch geringen Schatten in ihrem Wachstum, dem Biomasse-, Biogas- und Methanertrag sowie den qualitätsbestimmenden Inhaltsstoffen negativ beeinflusst.*

Während sich bereits im Pflanzenwachstum reduzierte Pflanzenhöhen und Blattflächenindizes zeigten, wirkte sich dies auch in einer Reduktion des finalen Biomasseertrages aus. Diese Reduktionen zeigten sich je nach Jahr ab 26 % bzw. 50 % Schatten. Eine Reduzierung der eingestrahlten Lichtmenge um 50 % resultierte in einer Halbierung der Erträge. Signifikante Reduktionen der Erträge waren bereits ab der geringsten Beschattung von 12 % zu beobachten. Hingegen stiegen Rohprotein und Rohasche ab 26 % Schatten an, was die Ausbeute von Biogas und Methan negativ beeinflusste. Die C4 Pflanze Mais zeigte sich daher als nicht empfehlenswert für Beschattungen von mehr als 26 %. Jedoch konnten selbst die nahezu halbierten Biomasseerträge unter der stärksten Beschattung höherer Erträge erreichen, als anderen Biomassekulturen unter voller Sonneneinstrahlung.

3. *Kartoffeln, die als schattentolerante Pflanzen bekannt sind, sind in der Lage mit geringeren Einstrahlungsmengen, hervorgerufen durch Beschattung, vergleichbare Erträge und Qualitäten zu erzeugen, wie unbeschattete Pflanzen. In ihrem Wachstum werden sich keine Unterschiede zeigen.*

Das Höhenwachstum der Kartoffeln wurde durch Schatten nicht beeinflusst. Die ertragsbestimmenden Parameter wie Pflanzenanzahl pro Quadratmeter und Stängelanzahl pro Pflanze wurden durch den Schatten nicht verändert. Eine Reduzierung der Knollenanzahl pro Pflanze und Knollenmasse pro Pflanze trat abhängig vom Jahr ein. Ebenso verhielt es sich mit dem Ertrag. Dieser wurde in einstrahlungsreichen Jahren gar nicht bzw. erst ab 50 % Schatten reduziert, während in einstrahlungsarmen Jahren ab 26 % Schatten Reduktionen eintraten. Die Qualität der Knollen wurde nicht beeinflusst. Unter Beschattungen zwischen 26 % – 50 % können Kartoffeln angebaut werden.

Um die Biodiversität zu erhalten, werden **alternative, herbizidsparende Formen der Unkrautbekämpfung** benötigt. Die Untersuchungen zur Etablierung einer KUP hatte gezeigt, dass manche Herbizidalternativen unter der einen Bodenbearbeitung besser wirkten, als unter einer anderen Bodenbearbeitung. Pflügen wirkte gut gegenüber Gräsern und durch die wendende Bodenbearbeitung wird die Bodensamenbank in tiefere Bodenschichten eingebracht, wodurch ungünstigere Keimbedingungen für die Unkräuter entstehen. Beim Einsatz dieser Form der Bodenbearbeitung sollten Herbizide mit einem breiten Wirkspektrum eingesetzt werden, sowohl im Vor- als auch im Nachauflauf. Dies reduziert zudem die Gefahr der Resistenzbildung. Mechanische Bodenbearbeitungen zwischen den Weidenreihen können, mit Ausnahme der Herbizidwalze, eine herbizideinsparende Etablierungsvariante sein. Die Untersaat in der Grubbervariante stellte für die Unkräuter eine Konkurrenz dar und unterdrückte diese. Diese Bodenbearbeitung benötigt eine flächige Herbizidapplikation, ansonsten ist die Konkurrenz für die Weiden zu hoch. Wenn keine Bodenbearbeitung erfolgt, keimen nur die Unkräuter aus den oberen Bodenschichten, dafür können alle Unkrautregulierungsvarianten eingesetzt werden, außer Mulchen zwischen den Weidenreihen.

Außer den untersuchten Kulturen Mais und Kartoffel, können andere **landwirtschaftliche Kulturen** ein interessanter Partner in AFS sein. Bei Getreiden, wie Weizen und Reis, beeinflusste der Schatten die ertragsbestimmenden Parameter negativ (Körner pro Ähre, Ähren pro m² und Tausendkornmasse). In Ölfrüchten, wie Sojabohne und Raps, reduzierte Schatten die Einlagerung von Assimilaten. Hingegen zeigten Leguminosen keine Ertragsreduktionen, sie kompensierten eine geringere Anzahl an Bohnen bzw. Körner durch eine höhere Tausendkornmasse. In Futterpflanzen wurden Veränderungen in der Qualität nachgewiesen, wobei C4 Pflanzen dafür anfälliger waren, als C3 Pflanzen. Dies zeigten auch die Ergebnisse der **Kapitel II** und **III**, Mais wurde durch Schatten stärker beeinflusst als Kartoffeln.

Neben der Konkurrenz um Licht sind zwei weitere Haupteinflussfaktoren die **Konkurrenz um Wasser und Nährstoffe**. Eine ausreichende Versorgung mit Wasser ist wichtig, da eine Reduktion dieser Versorgung zu einem gestörten Masse- und somit Nährstofftransport führt (besonders bei Stickstoff). Dieser führt zu einer reduzierten Blattfläche und einer damit einhergehenden verringerten photosynthetischen Effektivität. Für Mais kann dies dadurch nachgewiesen werden, dass die Biomasse reduziert ist und sich der Proteingehalt erhöht. Kartoffeln sind empfindlicher gegenüber Wassermangel, als gegenüber Stickstoffmangel. Eine geringe Verfügbarkeit von Wasser, besonders während den Phasen des Knollenansatzes und der Massebildung, führt zu kleineren Knollen mit einem erhöhten Stärkeanteil. Dies lässt den Schluss zu, dass Wasser der limitierende Faktor in semi-ariden Klimaten ist, während unter nördlicheren Breitengraden das Licht der limitierende Faktor ist.

Während AFS eine wichtige Förderung für die Biodiversität und Ökologie darstellt, ist die **Ökonomie** eines solchen Systems schwer zu ermitteln. Dies liegt an der langen Standzeit, besonders in Systemen die auf die Wertholzproduktion ausgelegt sind. Während dieser Zeit steigt der Einfluss der Bäume auf die landwirtschaftliche Kultur. Zudem sind die Preise für das Holz, die erst nach mehreren Dekaden anfallen, schwierig zu kalkulieren. Ein modellhaftes, ein Hektar großes AFS ergab für einen Reinbestand an Mais einen Gewinn von 801.38 € ha^{-1} $Jahr^{-1}$, während dieser Gewinn durch die Anlage von Wertholzstreifen um 8 % erhöht und bei Kurzumtriebsstreifen um 10 % reduziert würde. Bei Kartoffeln lagen die Gewinne im Reinbestand bei 7555.21 € ha^{-1} $Jahr^{-1}$, während sie durch die beiden verschiedenen Streifennutzungen um 19 % (Wertholz) und 9 % (Weiden-KUP) reduziert wurden. Die starke Reduktion bei den Kurzumtriebsstreifen wird durch die geringe Wirtschaftlichkeit bei dieser Systemgröße begründet. Bei den Wertholzstreifen wiederum ist es schwierig zu kalkulieren, da die Gewinne erst nach 60 Jahren oder mehr anfallen. In KUPs sind die geringen Preise für Hackschnitzel und der hohe manuelle Aufwand problematisch. Dies, in Kombination mit den landwirtschaftlichen Ertragsreduktionen alleine durch die Baumstreifen an sich, macht diese Form der Holznutzung in einem einen Hektar großen System unwirtschaftlich. Kartoffeln erzielen bereits einen so hohen Preis, dass bereits die geringste Ertragsreduktion zu signifikanten Reduktionen im Gewinn des ganzen Systems führen.

Ökologischen Vorteile welche durch AFS entstehen sind der reduzierte Einsatz von fossilen Energieträgern, da die Baumstreifen nicht mehr länger bearbeitet werden. Sowie die Kohlenstoffspeicherung durch die Bäume, die CO_2 aufnehmen und in ihrer Wurzelmasse speichern. Für das modellhafte, ein Hektar große System mit KUP-Streifen würde dies eine Kohlenstoffspeicherung von 11 Mg ha^{-1} $Jahr^{-1}$ bedeuten. Für AFS mit Wertholz wird die Kalkulation aufgrund der vielen verschiedenen Faktoren, die die Kohlenstoffspeicherung beeinflussen wesentlich komplexer (unterschiedlich alte Bäume im System, verschiedene Baumarten). Die Streifen bieten außerdem ein dauerhaftes Habitat für Bodenlebewesen und Vögel. Durch die Streifen kommt es zu einem Anstieg in der Arthropodenfauna, mehr Regenwürmer sind vorhanden, die die Bodeneigenschaften verbessern und mehr Vögel können in diesen Systemen nisten. Zudem kommt es in den Baumstreifen zu einer Verbesserung der Bodenstruktur durch eine geringe Lagerungsdichte und organischen Auflage, welche die Infiltration erhöhen und die Fließgeschwindigkeit des Wassers reduzieren, was Erosion entgegenwirkt. Auch verhindern die Baumstreifen die Auswaschung von Nährstoffen ins Grundwasser, für Nitrat kann dies eine Reduzierung von bis zu 30 % durch die Baumstreifen ausmachen. Durch die Aufnahme von CO_2 sorgen die Bäume für eine verbesserte Luftqualität, durch das Ausbleiben der Düngung in den Baumstreifen geht weniger Stickstoff als N_2O verloren und einige Bodenlebewesen in den Baumstreifen nutzen CH_4 als Kohlenstoffquelle.

Allerdings besteht **weiterer Forschungsbedarf**, der den Einfluss von Bäumen in verschiedenen Altersklassen auf landwirtschaftliche Kulturen ermittelt. Zudem kann die verwendete Methode der Beschattung mittels Netze optimiert werden, da die Beschattungsnetzen nicht ganz die Einstrahlungsbedingungen in einem AFS nachbilden können. Das Lichtspektrum unter Bäumen zeigt eine Reduzierung im roten Spektralbereich, während ein Anstieg im fernen Rotbereich durch die Absorption des Chlorophylls in den Baumblättern entsteht. Zudem muss ein dynamischer Versuchsaufbau gewählt werden, der den Verlauf von Sonne und Schatten im Verlauf des Tages und Jahres abbildet. Ein weiterer Fokus sollte auf verschiedenen Kulturarten liegen. Während in den ersten Jahren, wenn die Baumkronen noch klein sind und somit der Schatteneinfluss gering ist, herkömmliche landwirtschaftliche Kulturen angebaut werden können, kann in späteren Jahren mit größerem Schatteneinfluss der Anbau von Arznei-, Aroma-, Färbe- und Gewürzpflanzen interessant sein. Etliche dieser Pflanzen vertragen hohe Schatteneinflüsse auf Grund ihrer (teil-) schattigen Herkünfte aus Wäldern.

Es konnte gezeigt werden, dass es möglich ist mit AFS einen Beitrag zur Biodiversitätssteigerung zu schaffen. Durch den Einsatz aufeinander abgestimmter Bodenbearbeitungs- und Unkrautregulierungssystemen können fossile Kraftstoffe im Falle von reduzierter Bodenbearbeitungen eingespart werden. Die Ausbringung von Herbiziden in den Baumstreifen kann durch die alleinige Applikation in den Setzlingsreihen reduziert oder durch rein mechanische Alternativen ganz vermieden werden. In Wertholzstreifen erfolgt im Normalfall keine chemische Unkrautregulierung. Zusätzlich bieten die Baumstreifen Habitate und Nahrungsgrundlagen für kleine Wirbeltiere und zahlreiche Arthropodenklassen (Hymenoptera, Coleoptera, Lepidoptera und Diptera). Die dauerhafte Bepflanzung der Baumstreifen ermöglicht die Reduzierung von Klimagasen und kann so dem Klimawandel entgegenwirken. Deshalb sind AFS eine wertvolle Form der Landbewirtschaftung, um die derzeitigen Umweltprobleme sowohl auf nationaler als auch auf globaler Ebene zu reduzieren.

9 References

Allen, S.C., Jose, S., Nair, P.K.R., Brecke, B.J., Nkedi-Kizza, P., Ramsey, C.L., 2004. Safety-net role of tree roots: evidence from a pecan (Carya illinoensis K. Koch)–cotton (Gossypium hirsutum L.) alley cropping system in the southern United States. Forest Ecology and Management 192, 395–407. https://doi.org/10.1016/j.foreco.2004.02.009

Ayas, S., Korukçu, A., 2010. Water-yield relationships in deficit irrigated potato. Ziraat Fakültesi Dergisi, Uludağ Üniversitesi 24, 23–36.

Badr, M.A., El-Tohamy, W.A., Zaghloul, A.M., 2012. Yield and water use efficiency of potato grown under different irrigation and nitrogen levels in an arid region. Agricultural Water Management 110, 9–15.

Balandier, P., de Montard, F.-X., Curt, T., 2007. Root Competition for Water between Trees and Grass in a Silvopastoral Plot of 10 Year Old Prunus avium, in: Rani Batish, D., Kumar Kohli, R., Jose, S., Pal Singh, H. (Eds.), Ecological Basis of Agroforestry. CRC Press, pp. 253–270. https://doi.org/10.1201/9781420043365.ch13

Baligar, V.C., Fageria, N.K., He, Z.L., 2001. Nutrient Use Efficiency in Plants. Communications in Soil Science and Plant Analysis 32, 921–950. https://doi.org/10.1081/CSS-100104098

Bàrberi, P., Cascio, B.L., 2001. Long-term tillage and crop rotation effects on weed seedbank size and composition. Weed Research 41, 325–340. https://doi.org/10.1046/j.1365-3180.2001.00241.x

Barrios, E., Valencia, V., Jonsson, M., Brauman, A., Hairiah, K., Mortimer, P.E., Okubo, S., 2018. Contribution of trees to the conservation of biodiversity and ecosystem services in agricultural landscapes. International Journal of Biodiversity Science, Ecosystem Services & Management 14, 1–16.

Bártová, V., Bárta, J., Švajner, J., Diviš, J., 2012. Soil nitrogen variability in relation to seasonal nitrogen cycling and accumulation of nitrogenous components in starch processing potatoes. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science 62, 70–78. https://doi.org/10.1080/09064710.2011.577442

Beaudette, C., Bradley, R.L., Whalen, J.K., McVetty, P.B.E., Vessey, K., Smith, D.L., 2010. Tree-based intercropping does not compromise canola (Brassica napus L.) seed oil yield and reduces soil nitrous oxide emissions. Agriculture, Ecosystems & Environment 139, 33–39. https://doi.org/10.1016/j.agee.2010.06.014

Bélanger, J., Pilling, D., Commission on Genetic Resources for Food and Agriculture, Food and Agriculture Organization of the United Nations, 2019. The state of the world's biodiversity for food and agriculture.

Bender, B., Chalmin, A., Reeg, T., Konold, W., Mastel, K., Spiecker, 2009. Moderne Agroforstsysteme mit Werthölzern: Leitfaden für die Praxis. Bundesministerium für Bildung und Forschung.

Berg, Å., 2002. Breeding birds in short-rotation coppices on farmland in central Sweden—the importance of Salix height and adjacent habitats. Agriculture, Ecosystems & Environment 90, 265–276.

Bonanno, A., Materia, V.C., Venus, T., Wesseler, J., 2017. The Plant Protection Products (PPP) Sector in the European Union: A Special View on Herbicides. The European Journal of Development Research 29, 575–595. https://doi.org/10.1057/s41287-017-0088-1

Brix, M., Bender, B., Spiecker, H., 2009. Wertholzproduktion in Agroforstsystemen. Anbau und Nutzung von Bäumen auf Landwirtschaftlichen Flächen 251–261.

Carli, C., Yuldashev, F., Khalikov, D., Condori, B., Mares, V., Monneveux, P., 2014. Effect of different irrigation regimes on yield, water use efficiency and quality of potato (Solanum tuberosum L.) in the lowlands of Tashkent, Uzbekistan: a field and modeling perspective. Field Crops Research 163, 90–99.

C.A.R.M.E.N. e.V. - Hackschnitzel, 2019. Preisentwicklung bei Waldhackschnitzeln - der Energieholz-Index [WWW Document]. URL https://www.carmen-ev.de/infothek/preisindizes/hackschnitzel (accessed 4.6.19).

Carriedo, L.G., Maloof, J.N., Brady, S.M., 2016. Molecular control of crop shade avoidance. Current opinion in plant biology 30, 151–158.

Casal, J.J., 2012. Shade Avoidance. Arabidopsis Book 10. https://doi.org/10.1199/tab.0157

Ceccon, E., 2008. Production of bioenergy on small farms: a two-year agroforestry experiment using Eucalyptus urophylla intercropped with rice and beans in Minas Gerais, Brazil. New Forests 35, 285–298.

Chalmin, A., 2009a. Definition von Agroforstsystemen.

Chalmin, A., 2009b. Produktionsaspekte in Agroforstsystemen mit Werthölzern – Landwirtschaftliche Produktion. Anbau und Nutzung von Bäumen auf Landwirtschaftlichen Flächen, 275–288.

Cole, J.T., Cole, J.C., 2000. Ornamental Grass Growth Response to Three Shade Intensities. Journal of Environmental Horticulture 18, 18–22.

Copeland, N., Cape, J.N., Heal, M.R., 2012. Volatile organic compound emissions from Miscanthus and short rotation coppice willow bioenergy crops. Atmospheric Environment 60, 327–335. https://doi.org/10.1016/j.atmosenv.2012.06.065

Coppice Resources LTD (CRL), 2006. Grower's Guide to Short Rotation Coppice.

Cox, W.J., Kalonge, S., Cherney, D.J.R., Reid, W.S., 1993. Growth, Yield, and Quality of Forage Maize Under Different Nitrogen Management Practices. Agronomy Journal 85, 341. https://doi.org/10.2134/agronj1993.00021962008500020033x

den Herder, M., Moreno, G., Mosquera-Losada, R.M., Palma, J.H., Sidiropoulou, A., Freijanes, J.J.S., Crous-Duran, J., Paulo, J.A., Tomé, M., Pantera, A., 2017. Current extent and stratification of agroforestry in the European Union. Agriculture, Ecosystems & Environment 241, 121–132.

Department for Environment Food and Rural Affairs (DEFRA), 2004. Growing Short Rotation Coppice. Defra Publications, London.

Dimitriou, I., Busch, G., Jacobs, S., Schmidt-Walter, P., Lamersdorf, N., 2009. A review of the impacts of Short Rotation Coppice cultivation on water issues. Agriculture and Forestry Research 3, 197–206.

Dimitriou, I., Rutz, D., 2015. Suitable Short Rotation Coppice - A Handbook [WWW Document]. URL https://www.srcplus.eu/images/Handbook_SRCplus.pdf (accessed 2.2.19).

Douglas, G.B., McIvor, I.R., Lloyd-West, C.M., 2016. Early root development of field-grown poplar: effects of planting material and genotype. New Zealand Journal of Forestry Science 46. https://doi.org/10.1186/s40490-015-0057-4

Dufour, L., Metay, A., Talbot, G., Dupraz, C., 2013. Assessing Light Competition for Cereal Production in Temperate Agroforestry Systems using Experimentation and Crop Modelling. Journal of Agronomy and Crop Science 199, 217–227. https://doi.org/10.1111/jac.12008

Ekelöf, J., Guamán, V., Jensen, E.S., Persson, P., 2015. Inter-Row Subsoiling and Irrigation Increase Starch Potato Yield, Phosphorus Use Efficiency and Quality Parameters. Potato Research 58, 15–27. https://doi.org/10.1007/s11540-014-9261-5

Engels, W., Schulz, U., Radle, M., 1994. Use of the Tubingen mix for bee pasture in Germany.

Fageria, N.K., Baligar, V.C., Bailey, B.A., 2005. Role of cover crops in improving soil and row crop productivity. Communications in soil science and plant analysis 36, 2733–2757.

FAO, (Food and Agriculture Organization of the United Nations), 2019. Crop Information | Land & Water | Food and Agriculture Organization of the United Nations | Land & Water | Food and Agriculture Organization of the United Nations [WWW Document]. URL http://www.fao.org/land-water/databases-and-software/crop-information/en/ (accessed 3.9.19).

Feldman, S.R., Torres, C.A.P.S., Lewis, P., 1997. The effect of different tillage systems on the composition of the seedbank. Weed Research 37, 71–76. https://doi.org/10.1046/j.1365-3180.1996.d01-1.x

FlurbG - Flurbereinigungsgesetz [WWW Document], n.d. URL https://www.gesetze-im-internet.de/flurbg/BJNR005910953.html (accessed 1.31.19).

Forest Research, n.d. Short rotation coppice and energy crops [WWW Document]. Forest Research. URL http://www.forestresearch.gov.uk/tools-and-resources/historic-environment-resources/archaeological-preservation-during-woodland-expansion/short-rotation-coppice-and-energy-crops/ (accessed 11.9.19).

Franklin, K.A., Whitelam, G.C., 2005. Phytochromes and Shade-avoidance Responses in Plants. Ann Bot 96, 169–175. https://doi.org/10.1093/aob/mci165

Gaba, S., Gabriel, E., Chadø euf, J., Bonneu, F., Bretagnolle, V., 2016. Herbicides do not ensure for higher wheat yield, but eliminate rare plant species. Scientific reports 6, 30112.

Gao, L., Xu, H., Bi, H., Xi, W., Bao, B., Wang, X., Bi, C., Chang, Y., 2013. Intercropping Competition between Apple Trees and Crops in Agroforestry Systems on the Loess Plateau of China. PLoS ONE 8, e70739. https://doi.org/10.1371/journal.pone.0070739

Gao, S., Niu, Z., Huang, N., Hou, X., 2013. Estimating the Leaf Area Index, height and biomass of maize using HJ-1 and RADARSAT-2. International Journal of Applied Earth Observation and Geoinformation 24, 1–8. https://doi.org/10.1016/j.jag.2013.02.002

Gao, X., Li, C., Zhang, M., Wang, R., Chen, B., 2015. Controlled release urea improved the nitrogen use efficiency, yield and quality of potato (Solanum tuberosum L.) on silt loamy soil. Field Crops Research 181, 60–68. https://doi.org/10.1016/j.fcr.2015.07.009

Ghassemi-Golezani, K., Bakhshy, J., Zehtab-Salmasi, S., Moghaddam, M., 2013. Changes in leaf characteristics and grain yield of soybean (Glycine max L.) in response to shading and water stress. International Journal of Biosciences 3, 71–79.

Gheysari, M., Mirlatifi, S.M., Bannayan, M., Homaee, M., Hoogenboom, G., 2009. Interaction of water and nitrogen on maize grown for silage. Agricultural Water Management 96, 809–821. https://doi.org/10.1016/j.agwat.2008.11.003

Gosme, M., Mézière, D., Burgess, P., 2016. System Report: Durum Wheat Production in Agroforestry Systems in France.

Grabau, L.J., Van Sanford, D.A., Meng, Q.W., 1990. Reproductive characteristics of winter wheat cultivars subjected to postanthesis shading. Crop science 30, 771–774.

Guidi, W., Piccioni, E., Bonari, E., 2008. Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as vegetation filter. Bioresource technology 99, 4832–4840.

Habekotté, B., 1993. Quantitative analysis of pod formation, seed set and seed filling in winter oilseed rape (Brassica napus L.) under field conditions. Field Crops Research 35, 21–33. https://doi.org/10.1016/0378-4290(93)90133-8

Hadi, H., Ghassemi-Golezani, K., Khoei, F.R., Valizadeh, M., Shakiba, M.R., 2006. Response of Common Bean (Phaseolus vulgaris L.) to Different Levels of Shade. Journal of Agronomy 5, 595–599. https://doi.org/10.3923/ja.2006.595.599

Harrington, K.C., Ghanizadeh, H., 2017. Herbicide application using wiper applicators-A review. Crop Protection 102, 56–62.

Hartwig, N.L., Ammon, H.U., 2002. Cover crops and living mulches. Weed science 50, 688–699.

Heap, I., 2009. The international survey of herbicide resistant weeds. http://www. weedscience. com.

Herzog, F., 1998. Streuobst: a traditional agroforestry system as a model for agroforestry development in temperate Europe. Agroforestry systems 42, 61–80.

Islam, M.R., Garcia, S.C., Horadagoda, A., 2012. Effects of irrigation and rates and timing of nitrogen fertilizer on dry matter yield, proportions of plant fractions of maize and nutritive value and in vitro gas production characteristics of whole crop maize silage. Animal Feed Science and Technology 172, 125–135. https://doi.org/10.1016/j.anifeedsci.2011.11.013

Iwama, K., 2008. Physiology of the Potato: New Insights into Root System and Repercussions for Crop Management. Potato Research 51, 333–353. https://doi.org/10.1007/s11540-008-9120-3

Jenner, C.F., 1980. Effects of shading or removing spikelets in wheat: testing assumptions. Functional Plant Biology 7, 113–121.
Jodaugienė, D., Pupalienė, R., Urbonienė, M., Pranckietis, V., Pranckietienė, I., 2006. The impact of different types of organic mulches on weed emergence. Agronomy Research 4, 197–201.
Johansen, T.J., Thomsen, M.G., Løes, A.-K., Riley, H., 2015. Root development in potato and carrot crops – influences of soil compaction. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science 65, 182–192. https://doi.org/10.1080/09064710.2014.977942
Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agroforest Syst 76, 1–10. https://doi.org/10.1007/s10457-009-9229-7
Jose, S., Gillespie, A.R., Pallardy, S.G., 2004. Interspecific interactions in temperate agroforestry, in: New Vistas in Agroforestry. Springer, pp. 237–255.
Jose, S., Gillespie, A.R., Seifert, J.R., Biehle, D.J., 2000a. Defining competition vectors in a temperate alley cropping system in the midwestern USA: 2. Competition for water. Agroforestry systems 48, 41–59.
Jose, S., Gillespie, A.R., Seifert, J.R., Mengel, D.B., Pope, P.E., 2000b. Defining competition vectors in a temperate alley cropping system in the midwestern USA: 3. Competition for nitrogen and litter decomposition dynamics. Agroforestry Systems 48, 61–77.
Juhász, Á., Sepsi, P., Nagy, Z., Tõkei, L., Hrotkó, K., 2013. Water consumption of sweet cherry trees estimated by sap flow measurement. Scientia horticulturae 164, 41–49.
Jusoff, K., Elkawakib, S., Yunus, M., Ray, S.G., Rianda, B.L., 2013. The Development of Upland Red Rice under Shade Trees. World Applied Sciences Journal 24(1), 23-30.
Kaeser, A., Palma, J., Sereke, F., Herzog, F., 2010. Umweltleistungen von Agroforstwirtschaft. Die Bedeutung von Bäumen in der Landwirtschaft für Gewässer-und Bodenschutz, Klima, Biodiversität und Landschaftsbild. ART-Bericht 736, 1–12.
Kareem, I.A., 2007. Rattle Tree (Albizia Lebbeck) Effects On Soil Properties And Productivity Of Irish Potato (Solanum tuberosum) On The Jos Plateau, Nigeria (Thesis).
Karlen, D.L., Sadler, E.J., Camp, C.R., 1987. Dry Matter, Nitrogen, Phosphorus, and Potassium Accumulation Rates by Corn on Norfolk Loamy Sand. Agronomy Journal 79, 649. https://doi.org/10.2134/agronj1987.00021962007900040014x
Kefeli, V., Kalevitch, M.V., 2013. Chapter 7 - Natural Growth Inhibitors as Allelopathogens and Botanical Herbicides, in: Natural Growth Inhibitors and Phytohormones in Plants and Environment. Springer Science & Business Media.
Kephart, K.D., Buxton, D.R., Taylor, E.S., 1992. Growth of C3 and C4 perennial grasses under reduced irradiance. Crop Science 32, 1033–1038.
Khybri, M.L., Gupta, R.K., Ram, S., Tomar, H.P.S., 1992. Crop yields of rice and wheat grown in rotation as intercrops with three tree species in the outer hills of Western Himalaya. Agroforestry Systems 17, 193–204.
Kiziloglu, F.M., Sahin, U., Kuslu, Y., Tunc, T., 2009. Determining water–yield relationship, water use efficiency, crop and pan coefficients for silage maize in a semiarid region. Irrigation Science 27, 129–137. https://doi.org/10.1007/s00271-008-0127-y
Kizos, T., Plieninger, T., 2008. Agroforestry Systems Change In The Mediterranean: Some Evidence From Greek And Spainish Examples. In International conference" studying, modeling and sense making of planet Earth", Mytilene (pp. 1-6).
Knörzer, H., Müller, B.U., Guo, B., Graeff-Hönninger, S., Piepho, H.-P., Wang, P., Claupein, W., 2010. Extension and evaluation of intercropping field trials using spatial models. Agronomy journal 102, 1023–1031.
Kok, M.T.J., Alkemade, R., Bakkenes, M., van Eerdt, M., Janse, J., Mandryk, M., Kram, T., Lazarova, T., Meijer, J., van Oorschot, M., Westhoek, H., van der Zagt, R., van der Berg, M., van der Esch, S., Prins, A.-G., van Vuuren, D.P., 2018. Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. Biological Conservation 221, 137–150. https://doi.org/10.1016/j.biocon.2018.03.003
Kovács-Hostyánszki, A., Espíndola, A., Vanbergen, A.J., Settele, J., Kremen, C., Dicks, L.V., 2017. Ecological intensification to mitigate impacts of conventional intensive land use

on pollinators and pollination. Ecology Letters 20, 673–689. https://doi.org/10.1111/ele.12762

Krapp, A., 2015. Plant nitrogen assimilation and its regulation: a complex puzzle with missing pieces. Current opinion in plant biology 25, 115–122.

Lee, K.-H., Jose, S., 2003. Soil respiration and microbial biomass in a pecan — cotton alley cropping system in Southern USA. Agroforestry Systems 58, 45–54. https://doi.org/10.1023/A:1025404019211

Légère, A., Stevenson, F.C., Benoit, D.L., 2011. The Selective Memory of Weed Seedbanks after 18 Years of Conservation Tillage. Weed science 59(1), 98–106. https://doi.org/10.1614/WS-D-10-00092.1

LEL, 2018a. Kalkulationsdaten Marktfrüchte, Kalkulationsdaten. Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum Schwäbisch Gmünd (LEL), Schwäbisch Gmünd.

LEL, 2018b. Kalkulationsdaten Futterbau, Kalkulationsdaten. Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum Schwäbisch Gmünd (LEL), Schwäbisch Gmünd.

LEL, 2010. KUP-Rechner. Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum Schwäbisch Gmünd (LEL), Schwäbisch Gmünd.

Li, H., Jiang, D., Wollenweber, B., Dai, T., Cao, W., 2010. Effects of shading on morphology, physiology and grain yield of winter wheat. European Journal of Agronomy 33, 267–275.

Li, L., Ljung, K., Breton, G., Schmitz, R.J., Pruneda-Paz, J., Cowing-Zitron, C., Cole, B.J., Ivans, L.J., Pedmale, U.V., Jung, H.-S., Ecker, J.R., Kay, S.A., Chory, J., 2012. Linking photoreceptor excitation to changes in plant architecture. Genes & development 26(8), 785–790. https://doi.org/10.1101/gad.187849.112

Li, T.S.C., 1995. Asian and American Ginseng—A Review. HortTechnology 5, 27–34. https://doi.org/10.21273/HORTTECH.5.1.27

Li, Y., Craker, L.E., Potter, T., 1995. Effect of light level on essential oil production of sage (Salvia officinalis) and thyme (Thymus vulgaris), in: International Symposium on Medicinal and Aromatic Plants 426. pp. 419–426.

Lin, C.H., McGraw, M.L., George, M.F., Garrett, H.E., 2001a. Nutritive quality and morphological development under partial shade of some forage species with agroforestry potential. Agroforestry Systems 53, 269–281.

Lin, C.H., McGraw, M.L., George, M.F., Garrett, H.E., 2001b. Nutritive quality and morphological development under partial shade of some forage species with agroforestry potential. Agroforestry Systems 53, 269–281. https://doi.org/10.1023/A:1013323409839

Lin, S., Sattelmacher, B., Kutzmutz, E., Mühling, K.H., Dittert, K., 2004. Influence of Nitrogen Nutrition on Tuber Quality of Potato with Special Reference to the Pathway of Nitrate Transport into Tubers. Journal of Plant Nutrition 27, 341–350. https://doi.org/10.1081/PLN-120027658

Liu, Q., Xiu, W.U., Chen, B., Jie, G.A.O., others, 2014. Effects of low light on agronomic and physiological characteristics of rice including grain yield and quality. Rice Science 21, 243–251.

Livesley, S.J., Gregory, P.J., Buresh, R.J., 2002. Competition in tree row agroforestry systems. 2. Distribution, dynamics and uptake of soil inorganic N. Plant and Soil 247, 177–187.

Lovrić, M., Rois-Díaz, M., den Herder, M., Pisanelli, A., Lovrić, N., Burgess, P.J., 2018. Driving forces for agroforestry uptake in Mediterranean Europe: application of the analytic network process. Agroforest Systems 92(4), 863–876. https://doi.org/10.1007/s10457-018-0202-1

Lys, J.-A., Nentwig, W., 1992. Augmentation of beneficial arthropods by strip-management - 4. Surface activity, movements and acitivity density of abundant carabid beetles in a cereal field. Oecologia 92, 373–382.

Malghani, S., Reim, A., von Fischer, J., Conrad, R., Kuebler, K., Trumbore, S.E., 2016. Soil methanotroph abundance and community composition are not influenced by substrate availability in laboratory incubations. Soil Biology and Biochemistry 101, 184–194. https://doi.org/10.1016/j.soilbio.2016.07.009

Mantzanas, K., Papanastasis, V., Pantera, A., Papadopoulos, A., Burgess, P., 2016. System Description: Silvoarable Agroforestry in Greece.

Mariana, M., Hamdani, J.S., 2016. Growth and yield of Solanum tuberosum at medium plain with application of paclobutrazol and paranet shade. Agriculture and Agricultural Science Procedia 9, 26–30.

Marshall, E.J.P., Brown, V.K., Boatman, N.D., Lutman, P.J.W., Squire, G.R., Ward, L.K., 2003. The role of weeds in supporting biological diversity within crop fields. Weed research 43, 77–89.

Mary, F., Dupraz, C., Delannoy, E., Liagre, F., 1999. Incorporating agroforestry practices in the management of walnut plantations in Dauphiné, France: an analysis of farmers' motivations, in: Auclair, D., Dupraz, Christian (Eds.), Agroforestry for Sustainable Land-Use Fundamental Research and Modelling with Emphasis on Temperate and Mediterranean Applications. Springer Netherlands, Dordrecht, pp. 243–256. https://doi.org/10.1007/978-94-017-0679-7_15

McIntyre, B.D., Riha, S.J., Ong, C.K., 1997. Competition for water in a hedge-intercrop system. Field crops research 52, 151–160.

Ministerium für Ländlichen Raum und Verbraucherschutz (Ed.), 2015. Streuobstkonzeption Baden-Württemberg - Aktiv für Artenreichtum und Vielfalt unserer Streuobstlandschaften. Stuttgart.

Möller, R., Toonen, M., van Beilen, J., Salentijn, E., Clayton, D., 2007. Crop Platforms for Cell Wall Biorefining: Lignocellulose Feedstocks.

Montagnini, F., Nair, P.K.R., 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agroforestry systems 61, 281–295.

Moreno, G.M., Cáceres, Y., 2016. System report: Iberian Dehesa, Spain. EU AGFORWARD project (GA 613520). 53pp.

Morhart, C., Sheppard, J., Douglas, G.C., Lunny, R., Spiecker, H., Nahm, M., 2016. Wertholzproduktion in Agroforstsystemen – Ein Leitfaden für die Praxis. Professur für Waldwachstum, Freiburg im Breisgau.

Mosquera-Losada, M.R., Santiago Freijanes, J.J., Pisanelli, A., Rois, M., Smith, J., den Herder, M., Moreno, G., Malignier, N., Mirazo, J.R., Lamersdorf, N., 2016. Extent and success of current policy measures to promote agroforestry across Europe. AGFORWARD European project Policy Report.

Mu, H., Jiang, D., Wollenweber, B., Dai, T., Jing, Q., Cao, W., 2010. Long-term low radiation decreases leaf photosynthesis, photochemical efficiency and grain yield in winter wheat. Journal of Agronomy and Crop Science 196, 38–47.

Mutuo, P.K., Cadisch, G., Albrecht, A., Palm, C.A., Verchot, L., 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystems 71, 43–54. https://doi.org/10.1007/s10705-004-5285-6

Nadir, S.W., Ng'etich, W.K., Kebeney, S.J., 2018. Performance of crops under Eucalyptus tree-crop mixtures and its potential for adoption in agroforestry systems. Australian Journal of Crop Science 12, 1231.

Nair, P.R., 1985. Classification of agroforestry systems. Agroforestry systems 3, 97–128.

NASA, 2018. POWER Data Access Viewer [WWW Document]. URL https://power.larc.nasa.gov/data-access-viewer/ (accessed 11.1.18).

Nasrullahzadeh, S., Ghassemi-Golezani, K., Javanshir, A., Valizade, M., Shakiba, M.R., 2007. Effects of shade stress on ground cover and grain yield of faba bean (Vicia faba L.). Journal of Food Agriculture and Environment 5, 337.

Newman, S.M., Bennett, K., Wu, Y., 1997. Performance of maize, beans and ginger as intercrops in Paulownia plantations in China. Agroforestry Systems 39, 23–30.

Novoa, R., Loomis, R.S., 1981. Nitrogen and plant production. Plant and soil 58, 177–204.

Odhiambo, H.O., Ong, C.K., Deans, J.D., Wilson, J., Khan, A.A.H., Sprent, J.I., 2001. Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry system in Kenya. Plant and Soil 235, 221–233.

Ong, C.K., Corlett, J.E., Singh, R.P., Black, C.R., 1991. Above and below ground interactions in agroforestry systems. Forest Ecology and Management 45, 45–57.

Ong, C.K., Wilson, J., Deans, J.D., Mulayta, J., Raussen, T., Wajja-Musukwe, N., 2002. Tree–crop interactions: manipulation of water use and root function. Agricultural Water Management 53, 171–186. https://doi.org/10.1016/S0378-3774(01)00163-9

Oparka, K.J., Davies, H.V., Wright, K.M., Viola, R., Prior, D.A.M., 1990. Effect of sink isolation on sugar uptake and starch synthesis by potato-tuber storage parenchyma. Planta 182. https://doi.org/10.1007/BF00239992

Pagès, L., Pellerin, S., 1994. Evaluation of parameters describing the root system architecture of field grown maize plants (Zea mays L.). Plant and Soil 164, 169–176.

Palma, J.H.N., Graves, A.R., Bunce, R.G.H., Burgess, P.J., de Filippi, R., Keesman, K.J., van Keulen, H., Liagre, F., Mayus, M., Moreno, G., Reisner, Y., Herzog, F., 2007. Modeling environmental benefits of silvoarable agroforestry in Europe. Agriculture, Ecosystems & Environment 119, 320–334. https://doi.org/10.1016/j.agee.2006.07.021

Pantera, A., Papadopoulos, A., Kasselaki, M., Papanastasis, V., Mantzanas, K., Fotiadis, G., 2016. System report: agroforestry with orange groves in Crete, Greece.

Paris, P., Lauteri, M., Ciolfi, M., dalla Valle, C., Agricoltura, V., Mirck, A.J., Burgess, P., 2016. System Report: Trees for Timber with Arable Crops in Italy.

Parmenter, G., Littlejohn, R., 2000. Effect of shade on growth and photosynthesis of Panax ginseng. New Zealand Journal of Crop and Horticultural Science 28, 255–269. https://doi.org/10.1080/01140671.1997.9514147

Paulson, M., Bardos, P., Harmsen, J., Wilczek, J., Barton, M., Edwards, D., 2003. The practical use of short rotation coppice in land restoration. Land Contamination & Reclamation 11, 323–338. https://doi.org/10.2462/09670513.624

Peng, X., Zhang, Y., Cai, J., Jiang, Z., Zhang, S., 2009. Photosynthesis, growth and yield of soybean and maize in a tree-based agroforestry intercropping system on the Loess Plateau. Agroforestry systems 76, 569–577.

Petrillo, M., Herzog, F., ART, A.R.-T., Mirck, A.J., 2016. System report: Silvoarable agroforestry in Switzerland. AFROFORWARD Agroforestry for Europe. Agroscope Reckenholz-Tänikon.

Pio, C.A., Silva, P.A., Cerqueira, M.A., Nunes, T.V., 2005. Diurnal and seasonal emissions of volatile organic compounds from cork oak (Quercus suber) trees. Atmospheric Environment 39, 1817–1827. https://doi.org/10.1016/j.atmosenv.2004.11.018

Place, G., Reberg-Horton, C., 2008. Rotary Hoe: A Blind Cultivation Tool for In-Row Weed Control [WWW Document]. URL https://content.ces.ncsu.edu/static/publication/js/pdf_js/web/viewer.html?slug=rotary-hoe-a-blind-cultivation-tool-for-in-row-weed-control (accessed 2.14.19).

Plante, P.-M., Rivest, D., Vézina, A., Vanasse, A., 2014. Root distribution of different mature tree species growing on contrasting textured soils in temperate windbreaks. Plant and Soil 380, 429–439. https://doi.org/10.1007/s11104-014-2108-7

Pleijel, H., Danielsson, H., Vandermeiren, K., Blum, C., Colls, J., Ojanperä, K., 2002. Stomatal conductance and ozone exposure in relation to potato tuber yield—results from the European CHIP programme. European Journal of Agronomy 17, 303–317.

Proulx, R.A., Naeve, S.L., 2009. Pod removal, shade, and defoliation effects on soybean yield, protein, and oil. Agronomy Journal 101, 971–978.

Puértolas, J., Ballester, C., Elphinstone, E.D., Dodd, I.C., 2014. Two potato (Solanum tuberosum) varieties differ in drought tolerance due to differences in root growth at depth. Functional Plant Biology 41, 1107. https://doi.org/10.1071/FP14105

Puntel, L.A., 2012. Field characterization of maize photosynthesis response to light and leaf area index under different nitrogen levels: a modeling approach.

Putz, B., 1989. Kartoffeln: Züchtung, Anbau, Verwertung. Behr's Verlag DE.

Rahman, A., James, T.K., Mellsop, J., Grbavac, N., 2000. Effect of cultivation methods on weed seed distribution and seedling emergence. New Zealand Plant Protection 53, 28–33. https://doi.org/10.30843/nzpp.2000.53.3644

Rao, M.R., Palada, M.C., Becker, B.N., 2004. Medicinal and aromatic plants in agroforestry systems, in: Nair, P.K.R., Rao, M.R., Buck, L.E. (Eds.), New Vistas in Agroforestry: A Compendium for 1st World Congress of Agroforestry, 2004, Advances in Agroforestry. Springer Netherlands, Dordrecht, pp. 107–122. https://doi.org/10.1007/978-94-017-2424-1_8

Rathinasabapathi, B., Ferguson, J., Gal, M., 2005. Evaluation of allelopathic potential of wood chips for weed suppression in horticultural production systems. HortScience 40, 711–713.

Reynolds, P.E., Simpson, J.A., Thevathasan, N.V., Gordon, A.M., 2007. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecological Engineering 29, 362–371.

Rigueiro-Rodríguez, A., Fernández-Núñez, E., González-Hernández, P., McAdam, J.H., Mosquera-Losada, M.R., 2009. Agroforestry systems in Europe: productive, ecological and social perspectives, in: Agroforestry in Europe. Springer, pp. 43–65.

Roger-Estrade, J., Colbach, N., Leterme, P., Richard, G., Caneill, J., 2001. Modelling vertical and lateral weed seed movements during mouldboard ploughing with a skim-coulter. Soil and Tillage Research 63, 35–49.

Rosati, A., Mantovani, D., 2015. System Report: Intercropping of Olive Orchards in Italy.

Rosskopf, E., Morhart, C., Nahm, M., 2017. Modelling shadow using 3D tree models in high spatial and temporal resolution. Remote Sensing 9, 719.

Schoeneberger, M., Bentrup, G., de Gooijer, H., Soolanayakanahally, R., Sauer, T., Brandle, J., Zhou, X., Current, D., 2012. Branching out: Agroforestry as a climate change mitigation and adaptation tool for agriculture. Journal of Soil and Water Conservation 67, 128A-136A. https://doi.org/10.2489/jswc.67.5.128A

Schroth, G., Harvey, C.A., da Fonseca, G.A., Vasconcelos, H.L., Gascon, C., Izac, A.-M.N., 2004. Agroforestry and biodiversity conservation in tropical landscapes. Island Press.

Schulz, U., Brauner, O., Gru\s s, H., 2009. Animal diversity on short-rotation coppices–a review. Landbauforschung–vTI Agriculture and Forestry Research 59, 171–182.

Seobi, T., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Science Society of America Journal 69, 893–901.

Shanahan, J.F., Smith, D.H., Welsh, J.R., 1984. An Analysis of Post-Anthesis Sink-Limited Winter Wheat Grain Yields Under Various Environments1. Agronomy Journal 76, 611. https://doi.org/10.2134/agronj1984.00021962007600040025x

Sinclair, T.R., Jamieson, P.D., 2006. Grain number, wheat yield, and bottling beer: An analysis. Field Crops Research 98, 60–67. https://doi.org/10.1016/j.fcr.2005.12.006

Singh, R.P., Saharan, N., Ong, C.K., 1989. Above and below ground interactions in alley-cropping in semi-arid India. Agroforestry Systems 9, 259–274. https://doi.org/10.1007/BF00141088

Singh, S., 1994. Physiological response of different crop species to low light stress. Indian Journal of Plant Physiology 37, 147–147.

Smith, J., Pearce, B.D., Wolfe, M.S., 2013. Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renewable Agriculture and Food Systems 28, 80–92.

Smith, J., Venot, C., Mirck, A.J., Burgess, P., 2015. System Report: Silvoarable Agroforestry in the UK.

Stamps, W.T., Woods, T.W., Linit, M.J., Garrett, H.E., 2002. Arthropod diversity in alley cropped black walnut (Juglans nigra L.) stands in eastern Missouri, USA. Agroforestry Systems 56, 167–175.

Steduto, P., Hsiao, T.C., Fereres, E., Raes, D., 2012. Crop yield response to water, FAO irrigation and drainage paper. Food and Agriculture Organization of the United Nations, Rome.

Sudmeyer, R.A., Speijers, J., 2007. Influence of windbreak orientation, shade and rainfall interception on wheat and lupin growth in the absence of below-ground competition. Agroforestry Systems 71, 201–214. https://doi.org/10.1007/s10457-007-9070-9

Sun, D., Dickinson, G.R., 1994. A case study of shelterbelt effect on potato (Solanum tuberosum) yield on the Atherton Tablelands in tropical north Australia. Agroforest Syst 25, 141–151. https://doi.org/10.1007/BF00705674

Tayo, T.O., Morgan, D.G., 1979. Factors influencing flower and pod development in oil-seed rape (Brassica napus L.). The Journal of Agricultural Science 92, 363–373. https://doi.org/10.1017/S0021859600062894

Tein, B., Kauer, K., Eremeev, V., Luik, A., Selge, A., Loit, E., 2014. Farming systems affect potato (Solanum tuberosum L.) tuber and soil quality. Field Crops Research 156, 1–11. https://doi.org/10.1016/j.fcr.2013.10.012

Tezara, W., Mitchell, V.J., Driscoll, S.D., Lawlor, D.W., 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. Nature 401, 914–917. https://doi.org/10.1038/44842

Thevathasan, N.V., Gordon, A.M., 2004. Ecology of tree intercropping systems in the North temperate region: Experiences from southern Ontario, Canada, in: New Vistas in Agroforestry. Springer, pp. 257–268.

Tsonkova, P., Böhm, C., Quinkenstein, A., Freese, D., 2012. Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. Agroforestry Systems 85, 133–152. https://doi.org/10.1007/s10457-012-9494-8

Tu, M., Hurd, C., Randall, J.M., 2001. Weed Control Methods Handbook, The Nature Conservancy. Retrieved December 27, 2007.

Tubby, I., Armstrong, A., 2002. Establishment and management of short rotation coppice. Practice Note-Forestry Commission.

Udawatta, R.P., Garrett, H.E., Kallenbach, R.L., 2010. Agroforestry and grass buffer effects on water quality in grazed pastures. Agroforestry Systems 79, 81–87. https://doi.org/10.1007/s10457-010-9288-9

Unseld, R., Seidl, F., Nahm, M., Karopka, M., Zürcher, A., Möndel, A., 2014. Anlage und Bewirtschaftung von Kurzumtriebflächen in Baden-Württemberg - Eine praxisorientierte Handreichung.

Vandermeer, J.H., 1992. The ecology of intercropping. Cambridge University Press.

Varella, A.C., Moot, D.J., Pollock, K.M., Peri, P.L., Lucas, R.J., 2011. Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system? Agroforestry Systems 81, 157–173. https://doi.org/10.1007/s10457-010-9319-6

Verwijst, T., Lundkvist, A., Edelfeldt, S., Albertsson, J., 2013. Development of sustainable willow short rotation forestry in northern Europe, in: Biomass Now-Sustainable Growth and Use. InTech.

Vityi, A., Marosvölgyi, B., NyME, K.K.K., Kiss, S.A., Schettrer, P., Cooperative, K.D.A., Mirck, A.J., 2015. System report: Alley Cropping in Hungary.

Wardlaw, I.F., 1970. The early stages of grain development in wheat: response to light and temperature in a single variety. Australian Journal of Biological Sciences 23, 765–774.

White, A.C., Rogers, A., Rees, M., Osborne, C.P., 2016. How can we make plants grow faster? A source–sink perspective on growth rate. Journal of Experimental Botany 67(1), 31–45. https://doi.org/10.1093/jxb/erv447

Willemen, L., Hart, A., Negra, C., Harvey, C., Laestadius, L., Louman, B., Place, F., Winterbottom, R., Scherr, S.J., 2013. Taking tree-based ecosystem approaches to scale: evidence of drivers and impacts on food security, climate change resilience and carbon sequestration.

Zarzyńska, K., Boguszewska-Mankowsak, D., Nosalewicz, A., 2017. Differences in size and architecture of the potato cultivars root system and their tolerance to drought stress. Plant, Soil and Environment 63, 159–164. https://doi.org/10.17221/4/2017-PSE

Zervoudakis, G., Salahas, G., Kaspiris, G., Konstantopoulou, E., 2012. Influence of light intensity on growth and physiological characteristics of common sage (Salvia officinalis L.). Brazilian Archives of Biology and Technology 55, 89–95. https://doi.org/10.1590/S1516-89132012000100011

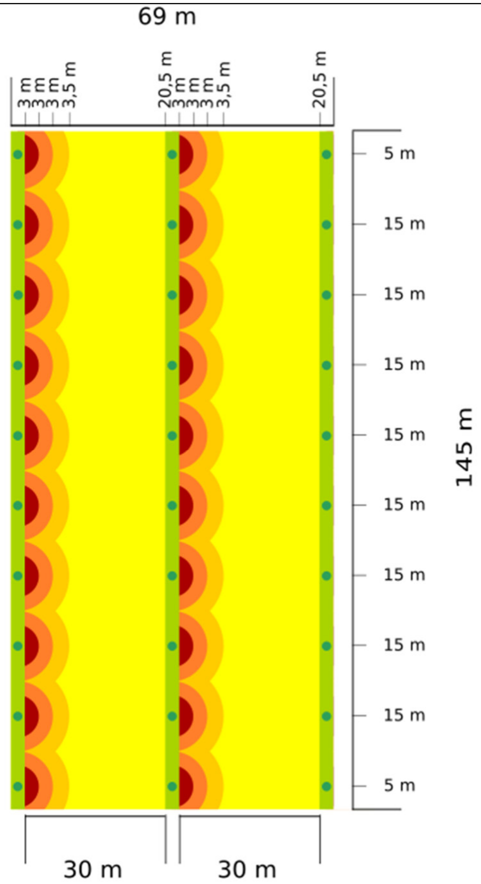
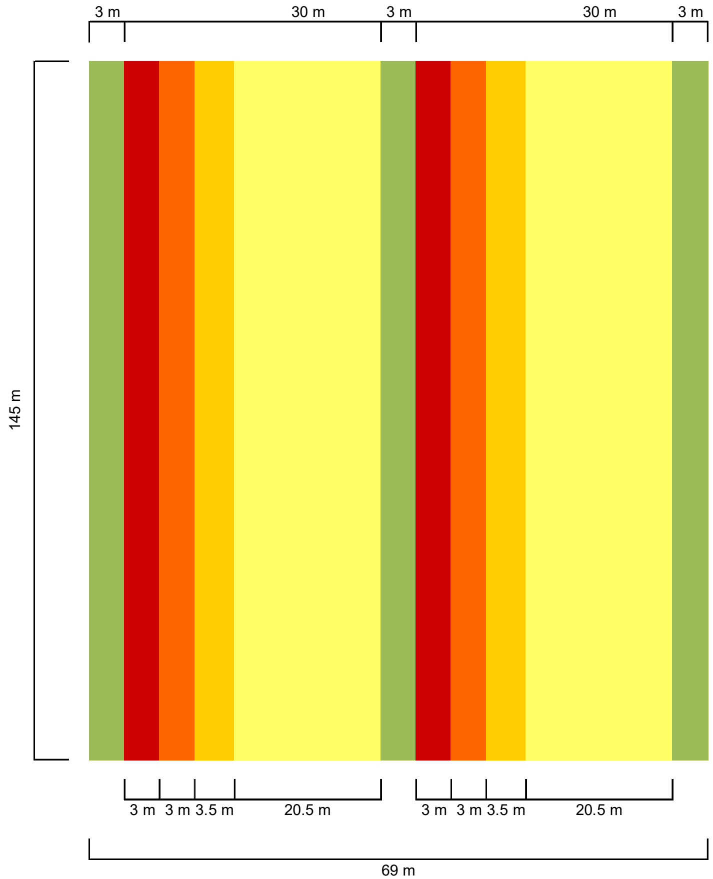
Zhang, W., Ahanbieke, P., Wang, B.J., Xu, W.L., Li, L.H., Christie, P., Li, L., 2013. Root distribution and interactions in jujube tree/wheat agroforestry system. Agroforestry systems 87, 929–939.

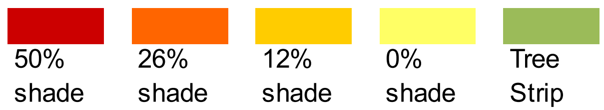
Zomer, R.J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M., Wang, M., 2016. Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. Scientific Reports 6. https://doi.org/10.1038/srep29987

Zomer, R.J., Trabucco, A., Coe, R., Place, F., 2009. Trees on farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper-World Agroforestry Centre.

Appendix

Table A 1: Assumptions for Economic Performance.

Timber-AFS	SRC-AFS
	



Tree Species		Sweet cherry (*Prunus avium* L.)	Willow (*Salix* sp.)
Field Size	m	145 x 69	145 x 69
Number of Crop Strips		2	2
Crop Strip Size	m	145 x 30	145 x 30
Number of Tree Strip		3	3
Plantation Design Trees		Single Row	4 rows per strip
Orientation of Tree Strip		E - W	E - W
Intra-row Distance	m	15	0.50
Inter-row Distance	m	33	0.75
Width Tree Strip	m	3	3
Tree Strip Size	m	145 x 3	145 x 3
Inter-strip Distance	m	30	30
Trees or Cuttings	ha^{-1}	30	1,164
Costs Planting Material	€ $tree^{-1}$ or € $cutting^{-1}$	5	0.12
Tree Guards	€ $tree^{-1}$	3.5	-
Planting Costs	€ $tree^{-1}$ or € $cutting^{-1}$	9.50	0.09
Replacement of Dead Trees	%	15	15
Wood Yield	m^3sub $tree^{-1}$ or t DM ha^{-1}	1.4	30
Price Wood	€ $m^{-3}sub^{-1}$ or € Mg DM^{-1}	400	144.2
Price By-Product	€ $m^{-3}sub^{-1}$	132	-
Costs of Mulching	€ m^{-2}	0.005	-
Working Time Mulching	h ha^{-1}	1	-
Cost Working Time	€ $man\text{-}hour^{-1}$	30	-
Pruning 3^{th} year	€ $tree^{-1}$	2.50	-
Pruning 6^{th} year	€ $tree^{-1}$	5.00	-
Pruning 8^{th} year	€ $tree^{-1}$	7.50	-
Pruning 10^{th} year	€ $tree^{-1}$	7.50	-
Costs per Harvest	€ $tree^{-1}$ or € ha^{-1}	102	2700
Recultivation Costs	€ ha^{-1}	130.50	130.50
Lifetime	yr	60	21

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Anlage 3

Eidesstattliche Versicherung über die eigenständig erbrachte Leistung

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Managing Trees on Arable Land
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2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht.

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Ich habe die Belehrung zur Eidesstattlichen Versicherung zur Kenntnis genommen.

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